Johnson Matthey Catalysts

CATALYTIC COATINGS FOR DIESEL PARTICULATE FILTER REGENERATION

Dr. Claus Görsmann
HDD OE Non-Road and Retrofit Technology Manager

EMISSION CONTROL TECHNOLOGIES

CONTENTS

- Introduction - catalytic coatings
- Regeneration of Diesel particulate filter systems
  - Oxygen and NO_2 based soot oxidation
    - Passive systems (NO_2 based, e.g. CRT®, CSF, CCRT®)
    - Active systems (O_2 based, e.g. ACRT®)
- Strategies for DPF systems with low NO_2 emissions
  - Low-NO_2 CRT® system
  - SCRT® retrofit systems: the most complete diesel emission control
- Conclusions

CATALYTIC COATINGS... (1/2)

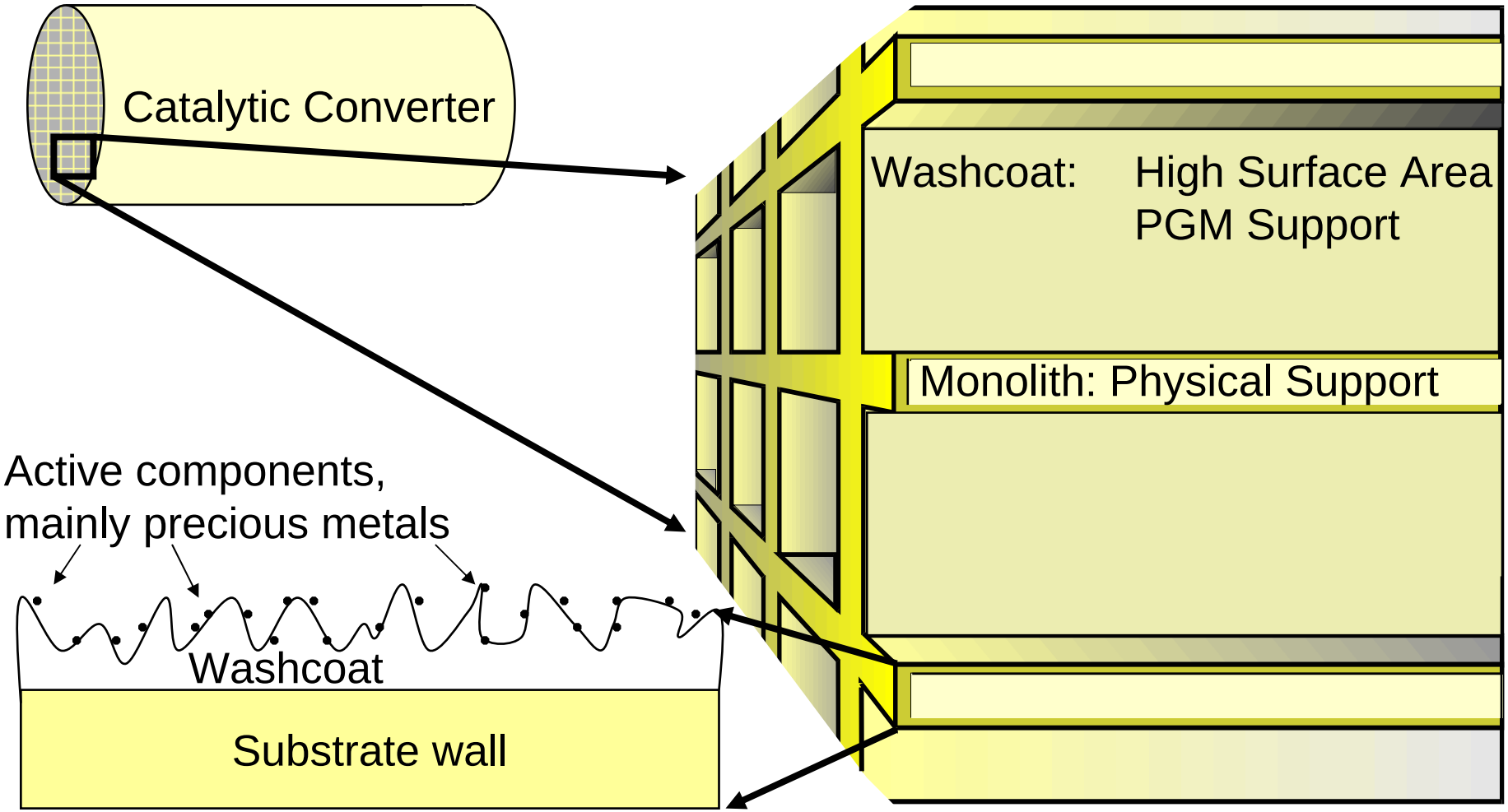
- Are a well proven and an essential part of Otto- and Diesel-engine exhaust aftertreatment systems

- Are used to clean-up Diesel emissions in
  - Millions of Diesel oxidation catalysts (standard in today‘s Diesel engine powered passenger cars)
  - Millions of Diesel engine powered passenger car soot filter systems
  - Hundreds of thousands of HDD soot filter systems
  - The vast majority of HDD retrofit soot filter systems

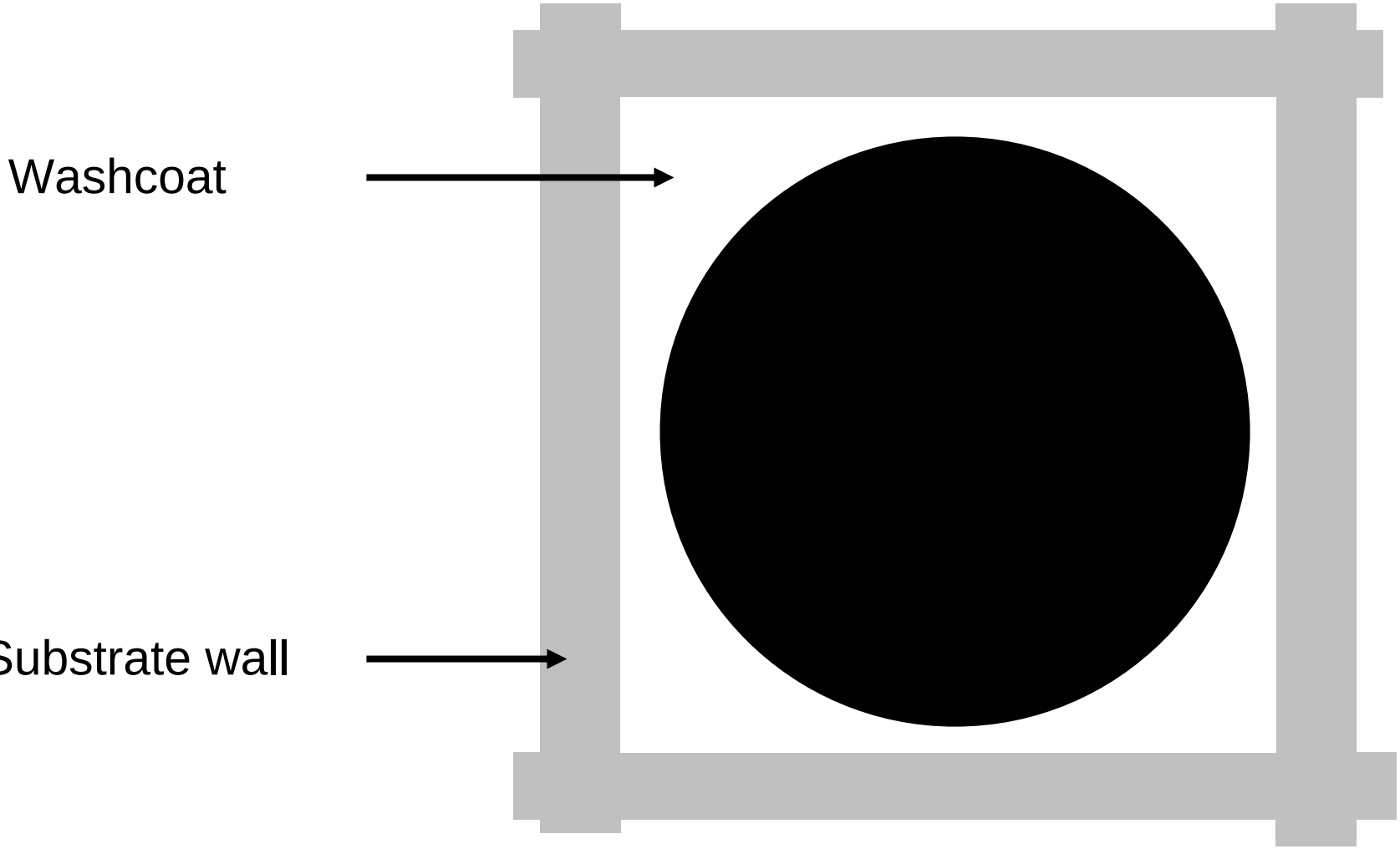
CATALYTIC COATINGS... (2/2)

- Are applied to surfaces within the exhaust aftertreatment system, mainly purpose-made substrates (flow through monoliths or wall flow filters).
  - Catalyst substrates typically consist of either Cordierite- or metal supports
  - Filter substrates are typically made of Silicon carbide (SiC), Cordierite or sintered metal
- Consist of active components (mainly precious metals) and components (mainly non precious metal oxides), which enhance the efficiency and stability of the active components. These components are called “washcoat”.

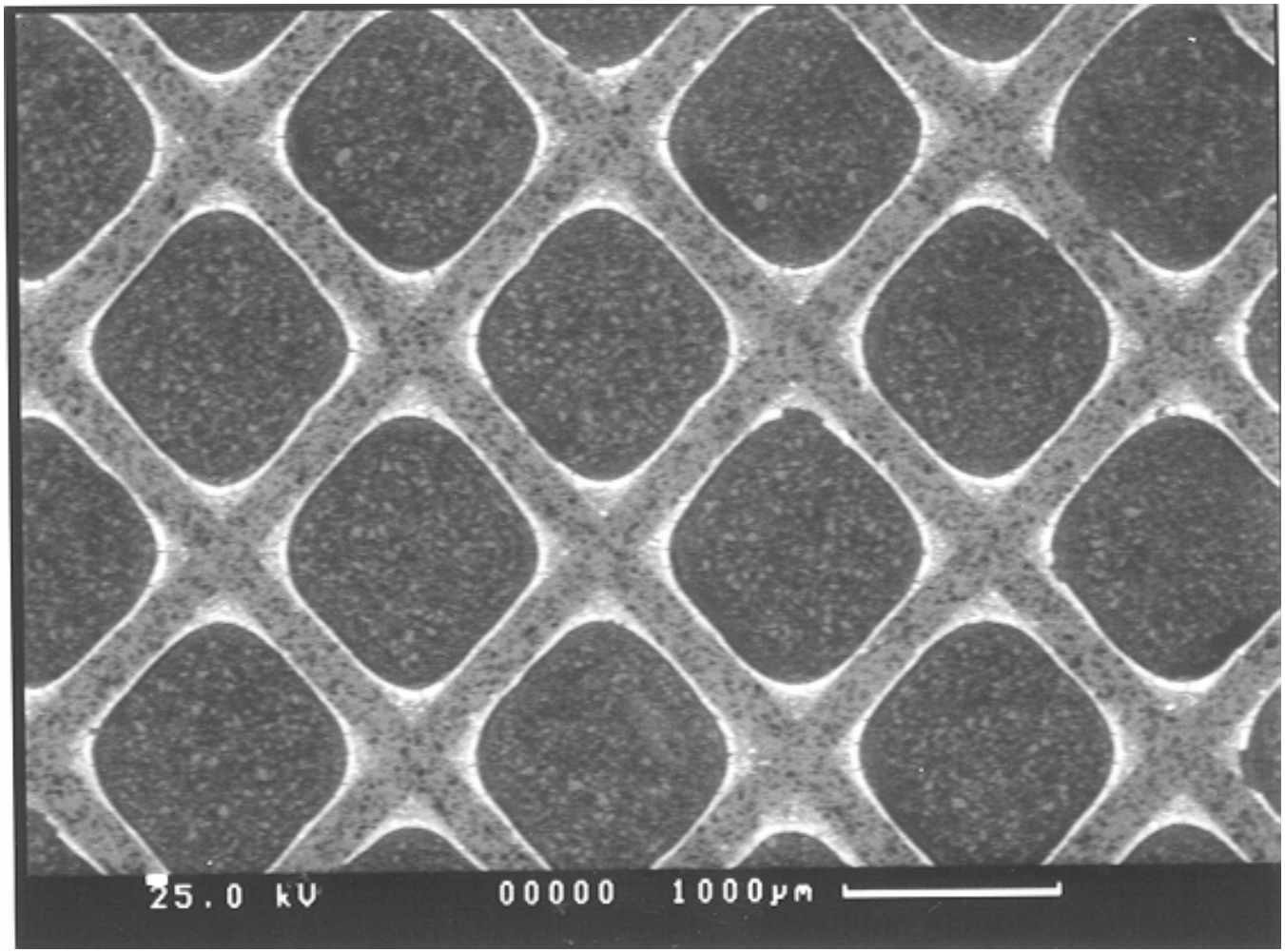
STRUCTURE OF A CATALYTIC CONVERTER



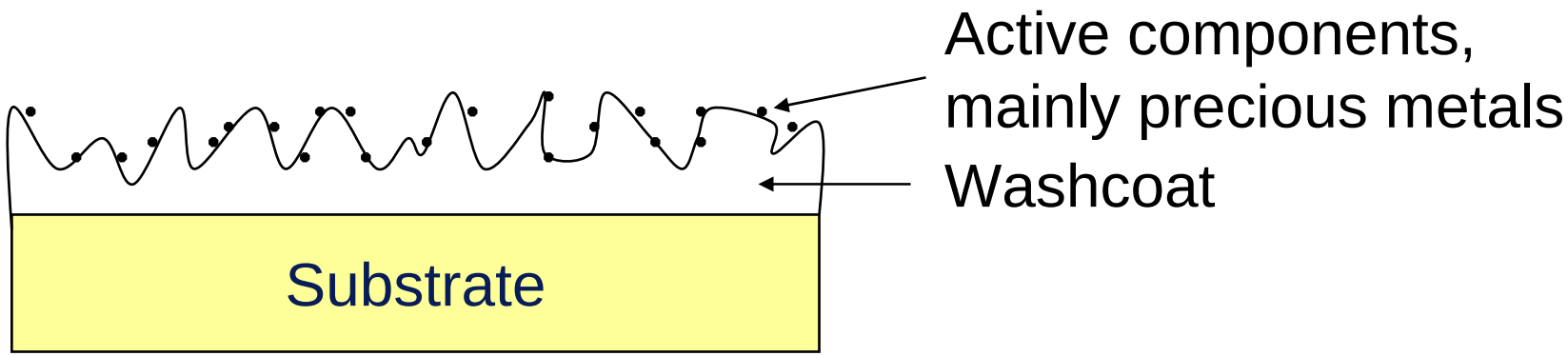
SCHEMATIC: CHANNEL IN CATALYST (AXIAL VIEW)



SEM IMAGE OF COATED SUBSTRATE



TYPICAL DATA FOR CATALYTIC COATINGS



- Typical...
  - Specific surface are of the substrate: 0.1-1m²/g
  - Specific surface area of washcoat: 50-500m²/g
  - Washcoat loading: 20-200g/litre catalyst volume
  - Washcoat thickness: 0.01-0.2mm
  - Loading of active components: 0.01-10g/litre catalyst volume

GENERAL REQUIREMENTS FOR CATALYTIC COATINGS

- High catalytic activity (and sometimes also high selectivity e.g. for SCR catalysts)
- High chemical and thermal stability
- Minimal influence on exhaust backpressure (especially for coatings on filter)

The means to meet these targets are contradictory and require compromises in order to achieve application optimised systems.

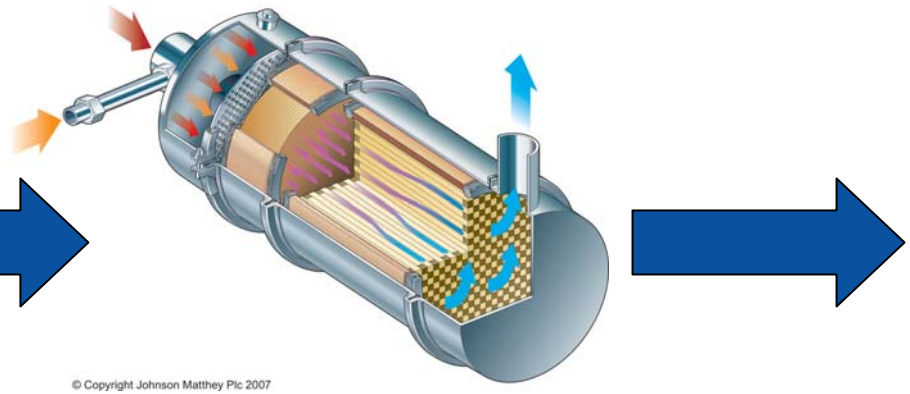
CONTENTS

- Introduction - catalytic coatings
- Regeneration of Diesel particulate filter systems
  - Oxygen and NO_2 based soot oxidation
    - Passive systems (NO_2 based, e.g. CRT®, CSF, CCRT®)
    - Active systems (O_2 based, e.g. ACRT®)
- Strategies for DPF systems with low NO_2 emissions
  - Low-NO_2 CRT® system
  - SCRT® retrofit systems: the most complete diesel emission control
- Conclusions

PM CONTROL: DIESEL PARTICULATE FILTER SYSTEMS

PM

NO_X



NO_X

- Soot filtration efficiency
  - Partial filtration
  - Full filtration
- Regeneration
  - Passive (NO_2 based)
  - Active (O_2 or NO_2 based)
  - Burner Systems

REGENERATION OF DIESEL PARTICULATE FILTER SYSTEMS: FORMING OF GASEOUS PRODUCTS

Evaporation and Decomposition trough heat

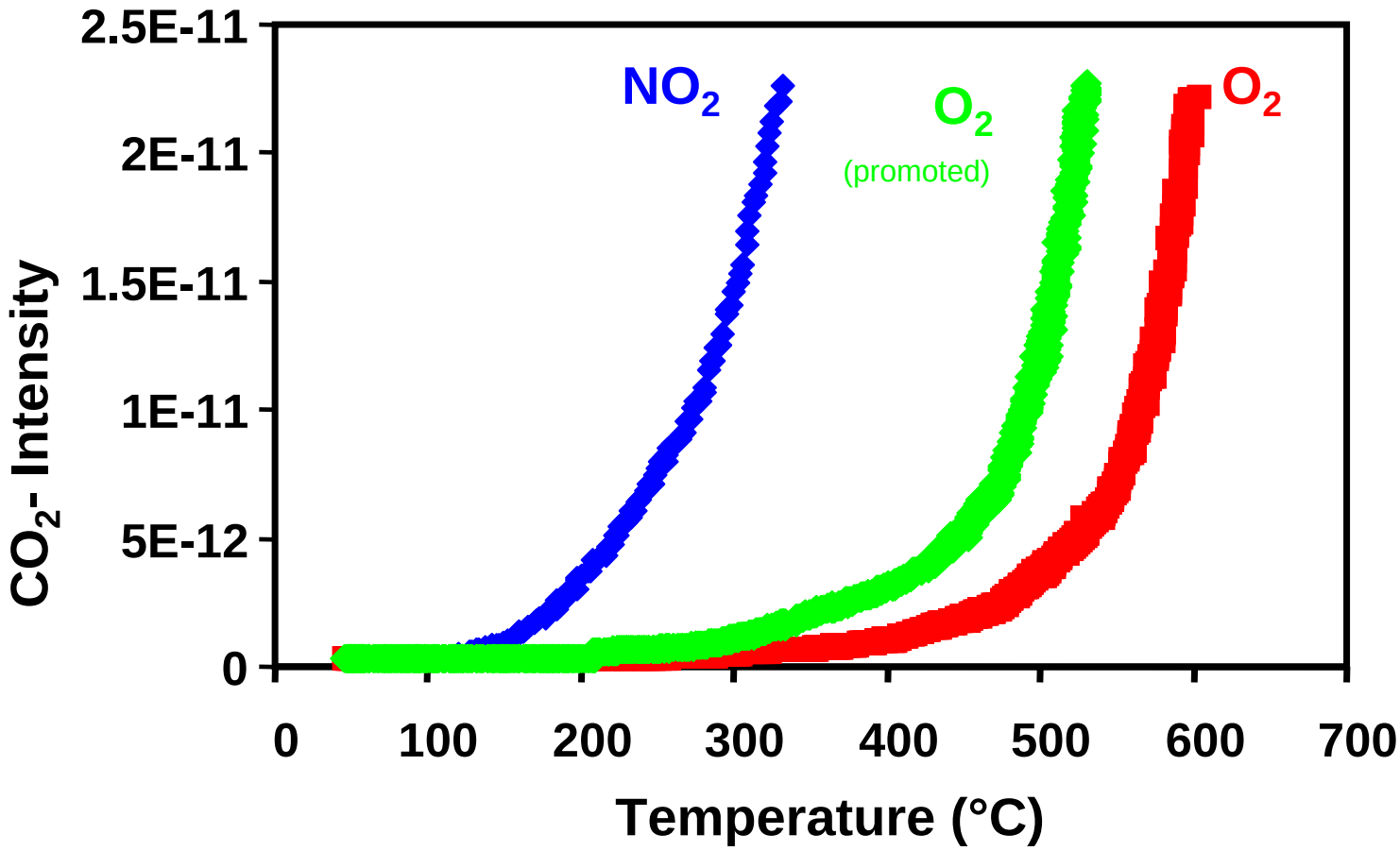
- $H_2O(l) \rightarrow H_2O(g)$ (1)
- $H_2SO_4 \rightarrow SO_2 + H_2O + ½\ O_2$ (2)
- $2\ HNO_3 \rightarrow 2\ NO_2 + H_2O + ½\ O_2$ (3)

Oxidation of soot through Oxygen via O_2 or NO_2

- $C + 2$ "O" $\rightarrow CO_2$ (4)
- $C + O_2 \rightarrow CO_2$ (4a)
- $C + 2\ NO_2 \rightarrow CO_2 + 2\ NO$ (4b)

- $C_XH_Y + (2x+y/2)$ "O" $\rightarrow$ x CO2 + y/2 H_2O (5)

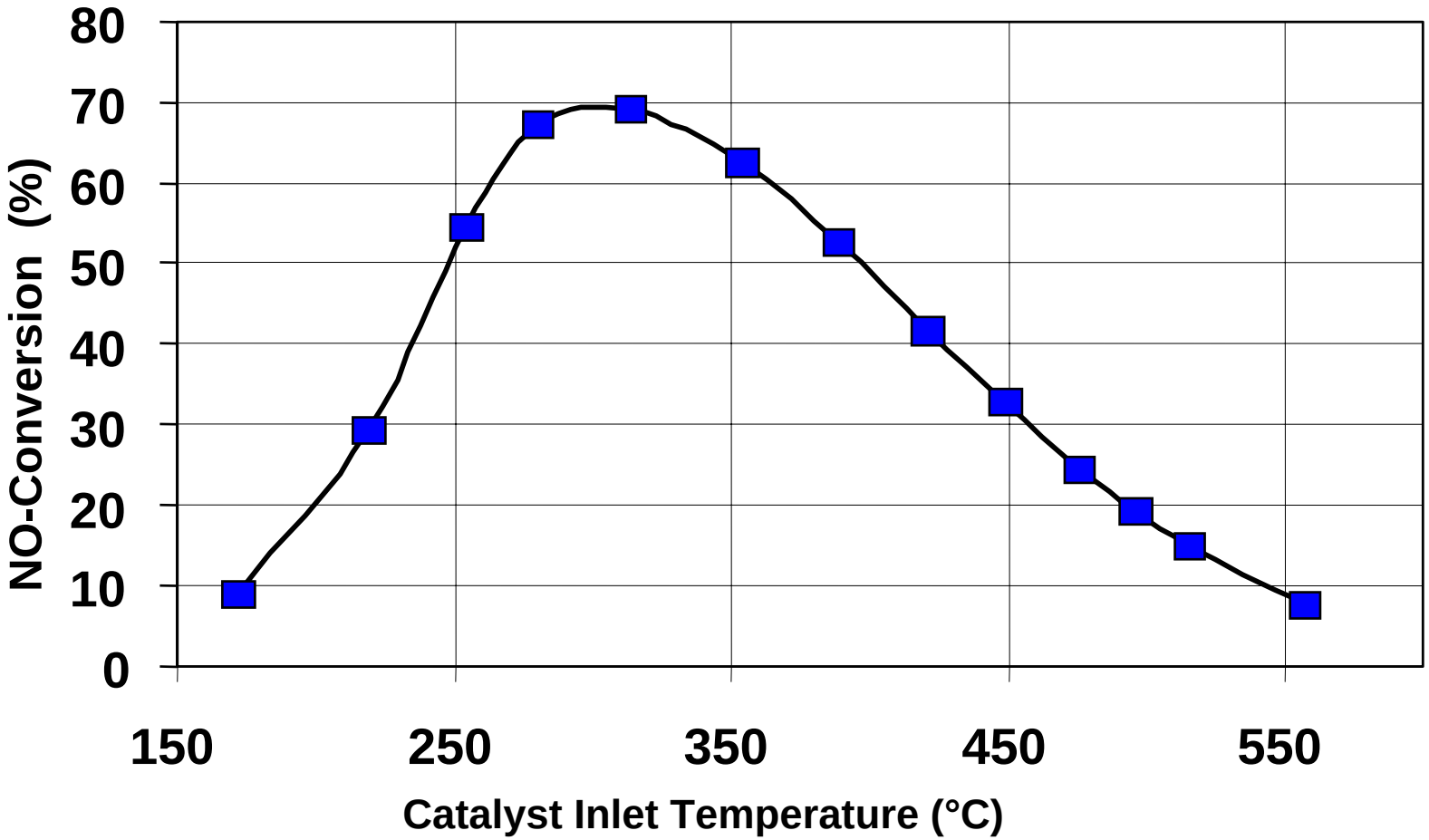
SOOT COMBUSTION (TO CO_2) BY NO_2 AND O_2 AS A FUNCTION OF TEMPERATURE



CONTENTS

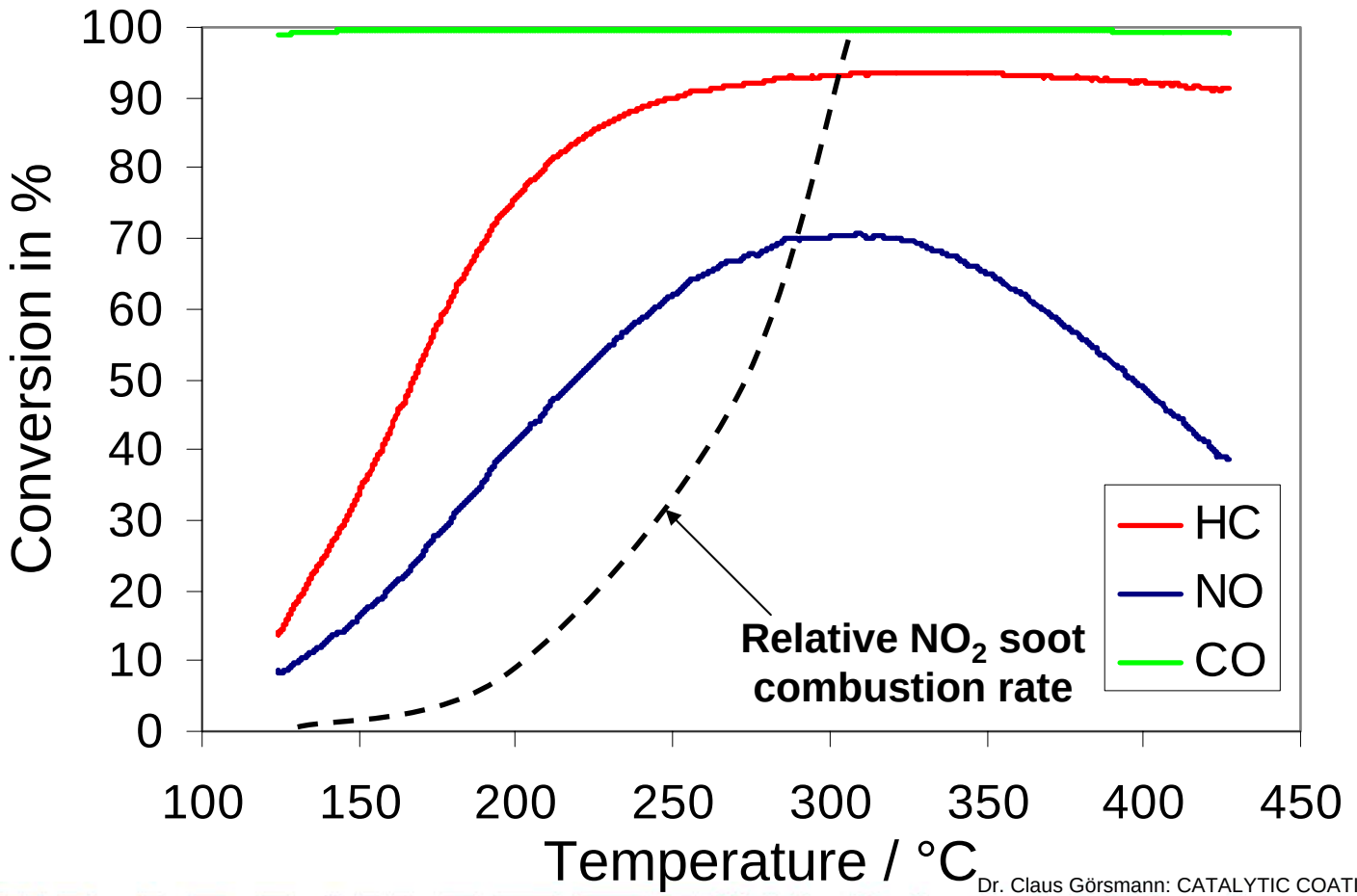
- Introduction - catalytic coatings
- Regeneration of Diesel particulate filter systems
  - Oxygen and NO_2 based soot oxidation
    - Passive systems (NO_2 based, e.g. CRT®, CSF, CCRT®)
    - Active systems (O_2 based, e.g. ACRT®)
- Strategies for DPF systems with low NO_2 emissions
  - Low-NO_2 CRT® system
  - SCRT® retrofit systems: the most complete diesel emission control
- Conclusions

NO CONVERSION TO NO_2 OVER A DOC

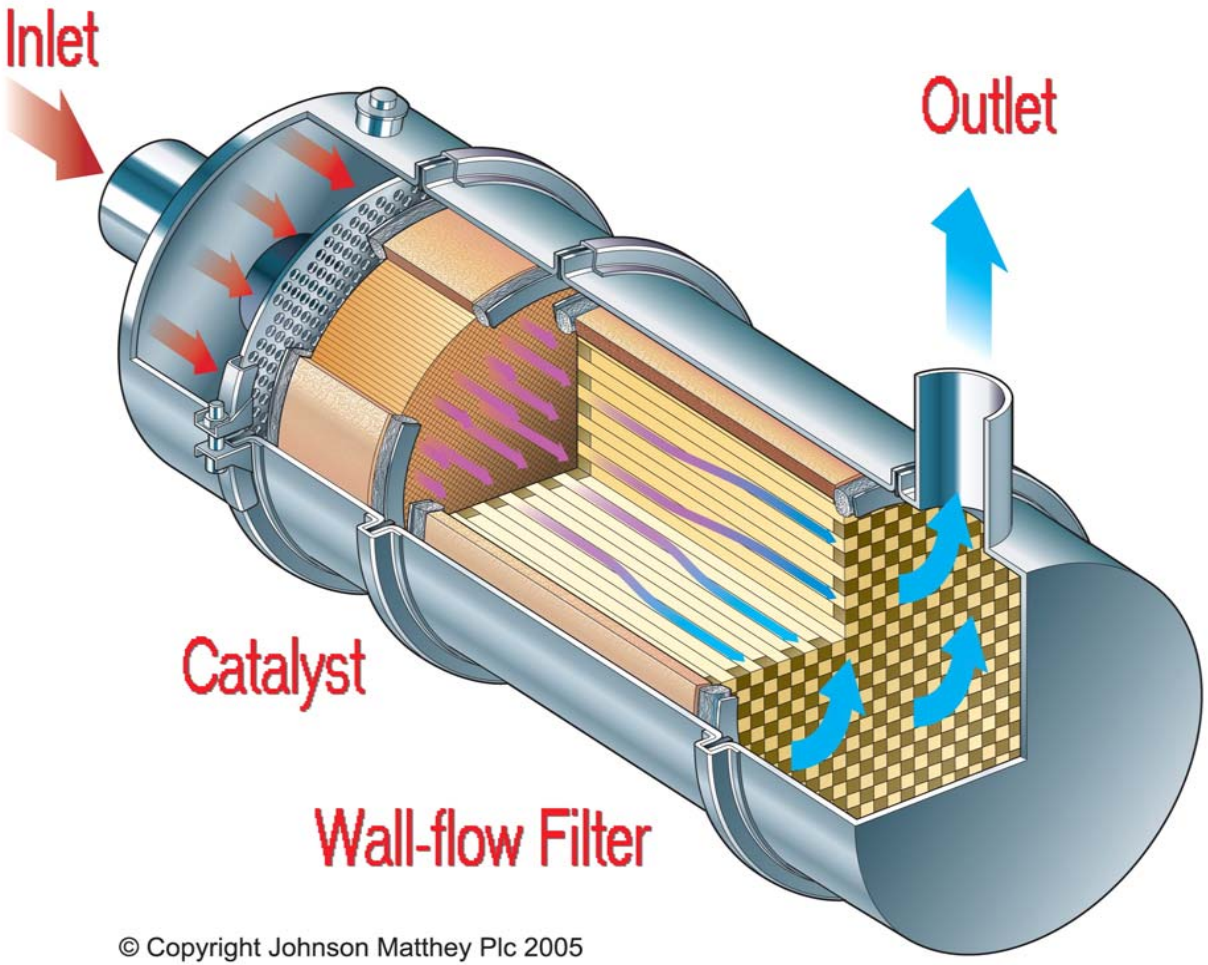


PASSIVE DOC PERFORMANCE

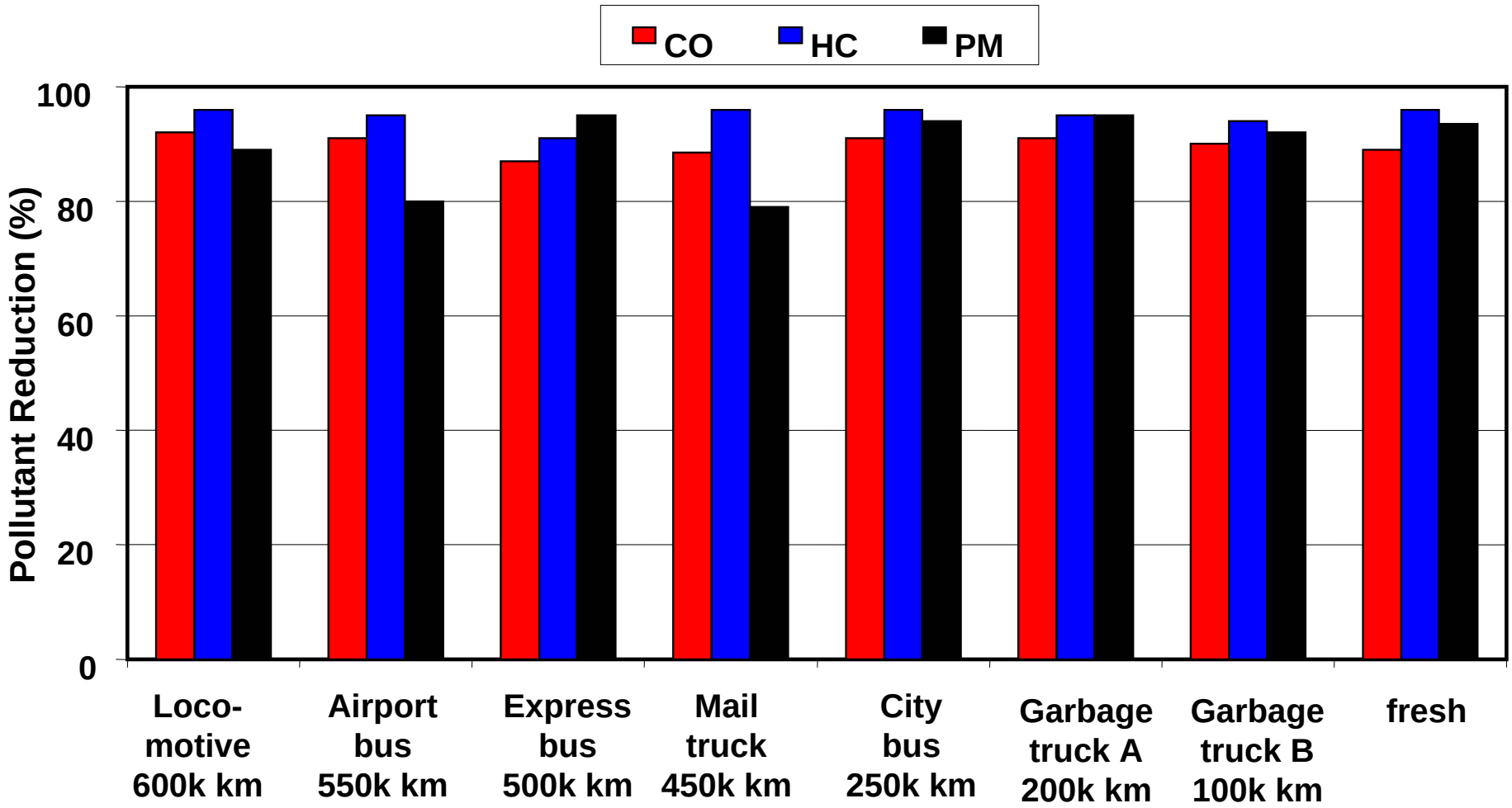
- Typical light-off conversion profile for a DOC catalyst



CRT® SCHEMATIC DRAWING

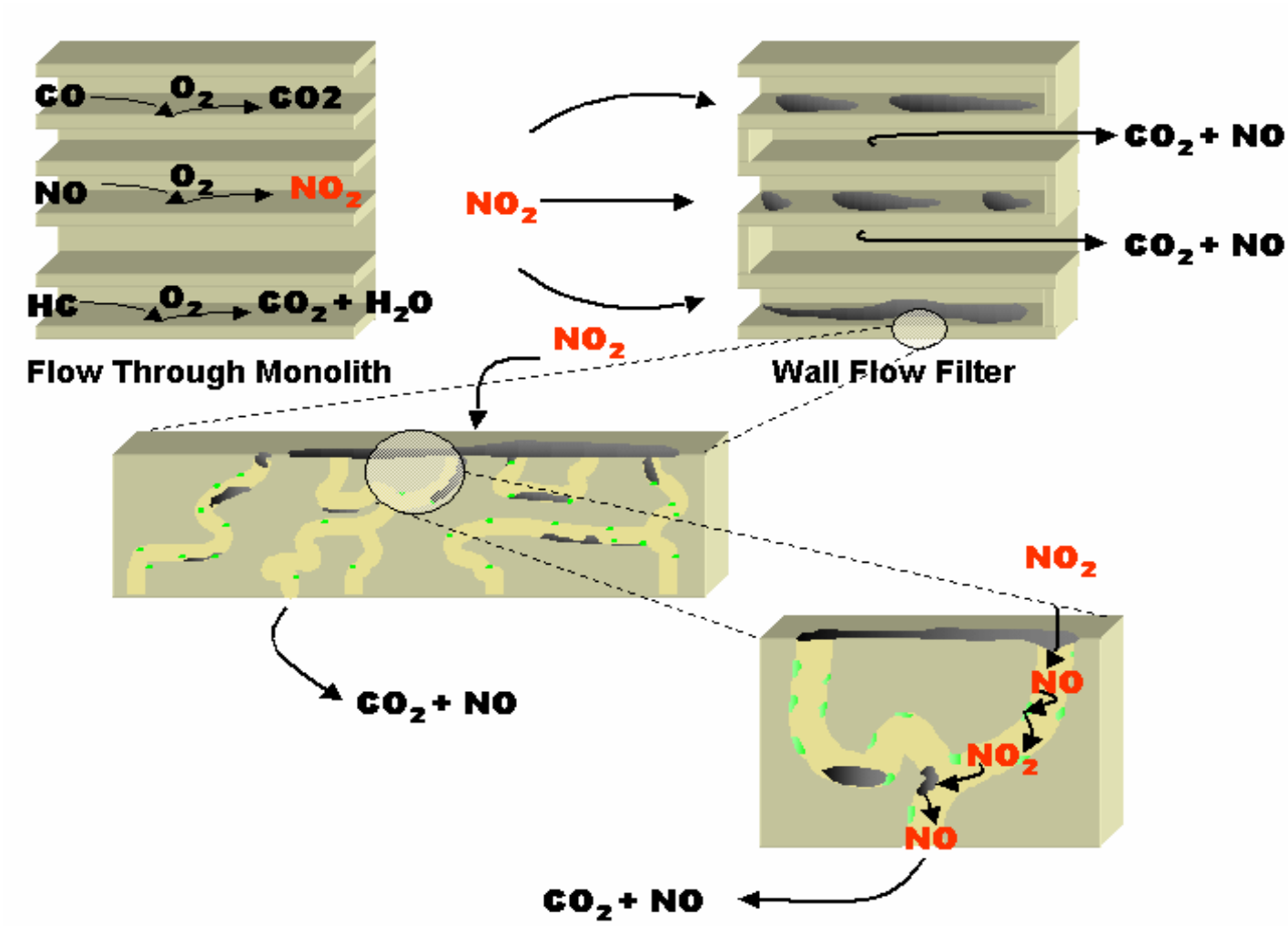


FIELD EXPERIENCE CRT®
- POLLUTANT REDUCTION

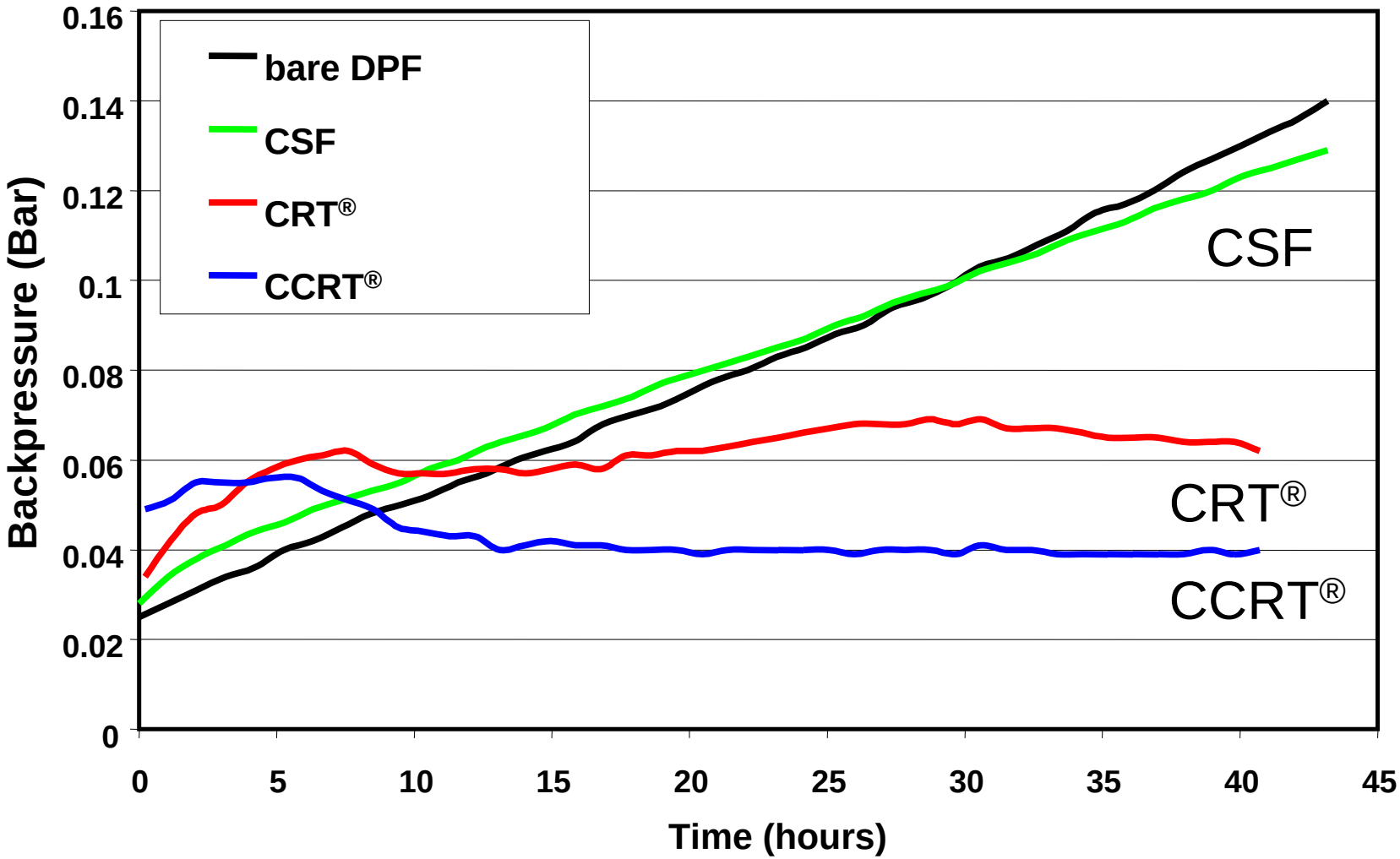


PRINCIPLE CRT®, CSF AND CCRT®

Confidential



PERFORMANCE OVER LOW TEMPERATURE CYCLE (T < 270°C)



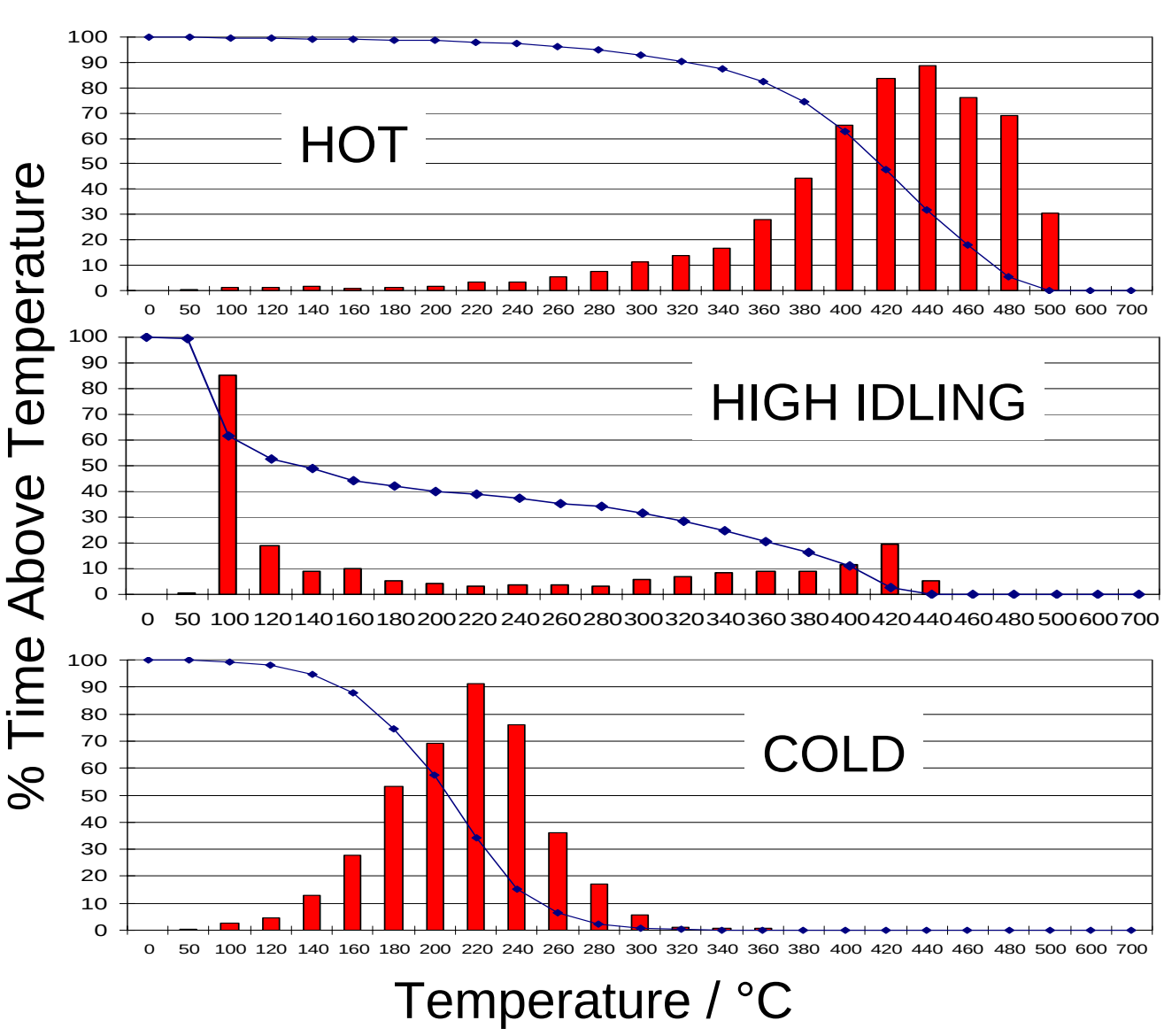
EXPERIENCE FROM ON-ROAD SYSTEMS

- Europe (EU IV and EU V)
  - SCR: total market so far ca. 450,000
  - EGR + DOC (+ partial DPF): total market so far ca. 200,000
- USA (EPA 2007): total market so far ca. 375,000
  - DOC + CSF
  - Burner + CSF
- Systems under development to meet future Japanese (JP09), US (EPA 2010) and European (EU VI) legislation will combine PM control with NOx aftertreatment.
- Non-road emissions aftertreatment systems can benefit from the experience from on-road applications.

DPF-SYSTEMS RETROFIT EXPERIENCE

- Of the 150,000 HDD vehicles retrofitted with JM DPF systems globally, there are several thousand non-road machines in Europe (mainly Switzerland) and USA.
- By far the most successful non-road retrofit systems are the purely passive systems CRT® (DOC+DPF) and CCRT® (DOC + coated DPF).
- Electrically regenerating systems (“DPFi“) have been applied in combination with a CRT® or fuel borne catalyst in applications, which are not suitable for passive regeneration (too cold and/or unfavorable NO_X/PM ratio or too dirty).

EXAMPLES FOR VERY DIFFERENT DUTY CYCLES



EXAMPLES: CRT® ON NON-ROAD EQUIPMENT

CAT 657 E Scraper Retrofit

CASE MX100 Tractor

CAT 966 G2 Excavator

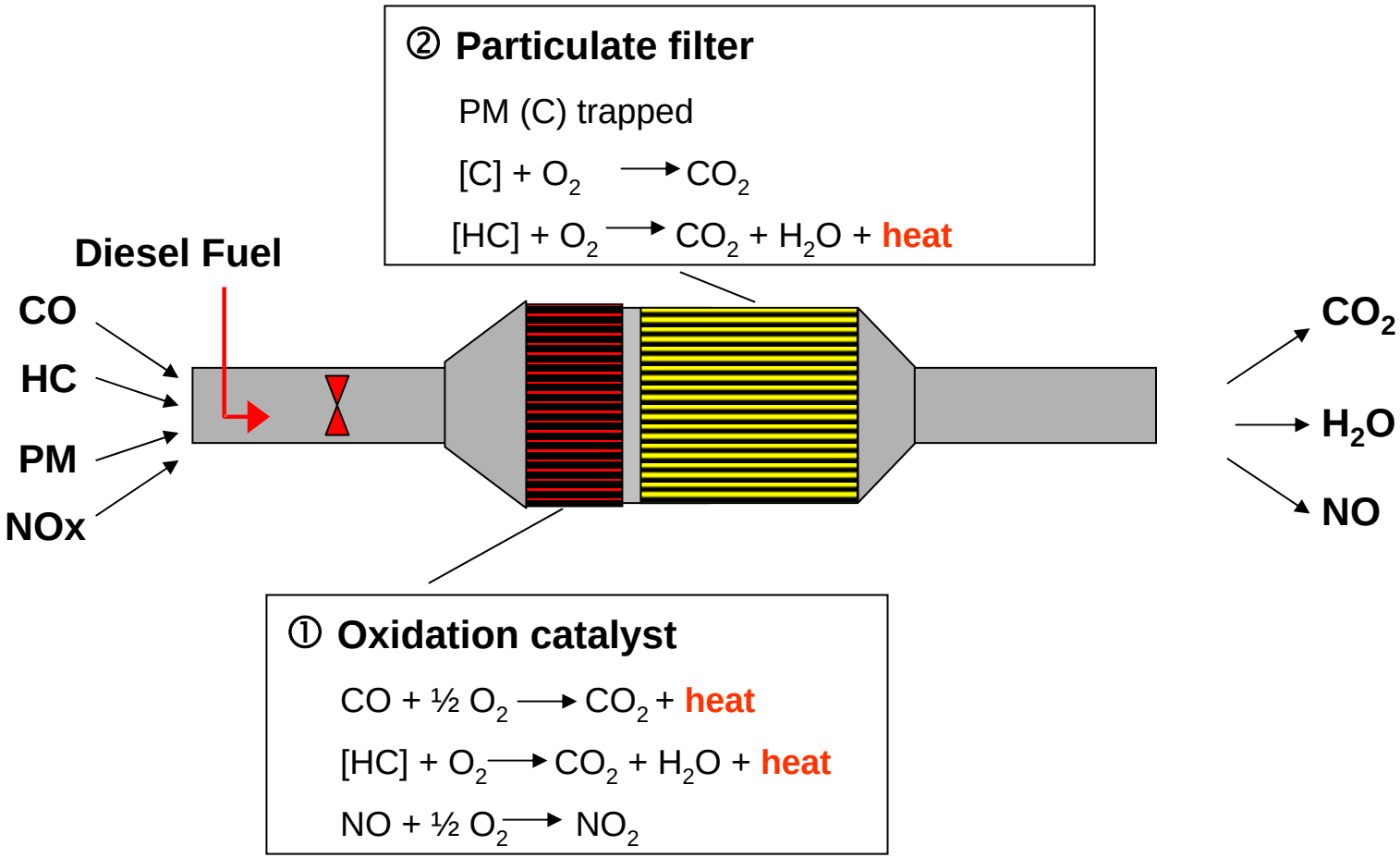
EXAMPLE: CRT® SYSTEM ON TRACTOR

Confidential

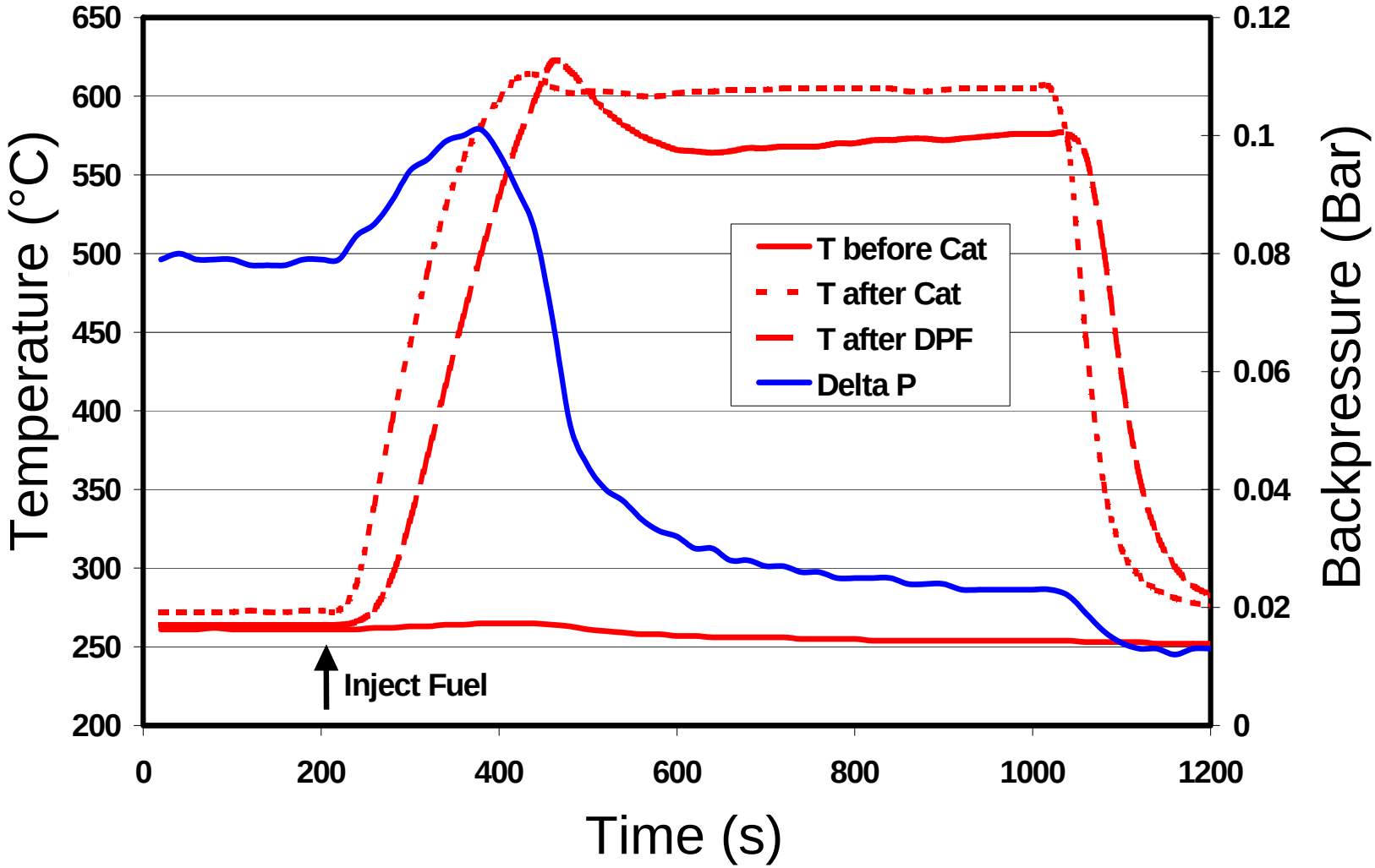
CONTENTS

- Introduction - catalytic coatings
- Regeneration of Diesel particulate filter systems
  - Oxygen and NO_2 based soot oxidation
    - Passive systems (NO_2 based, e.g. CRT®, CSF, CCRT®)
    - Active systems (O_2 based, e.g. ACRT®)
- Strategies for DPF systems with low NO_2 emissions
  - Low-NO_2 CRT® system
  - SCRT® retrofit systems: the most complete diesel emission control
- Conclusions

PRINCIPLE OF ACTIVE REGENERATION UTILISING CATALYTIC COMBUSTION

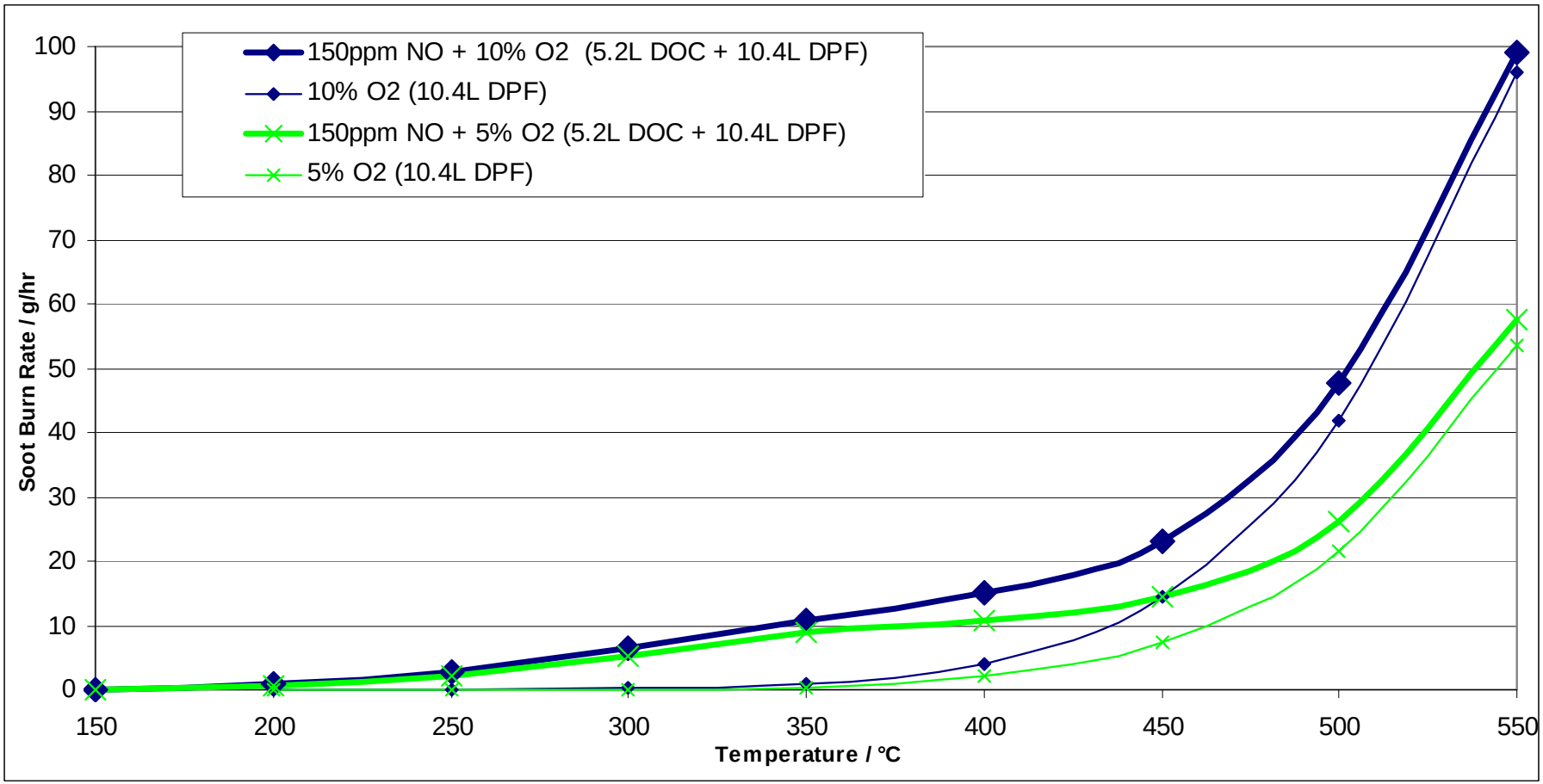


ACTIVE REGENERATION OF A CRT® WITH O_2 (105 g SOOT ON 17-LITRE DPF)

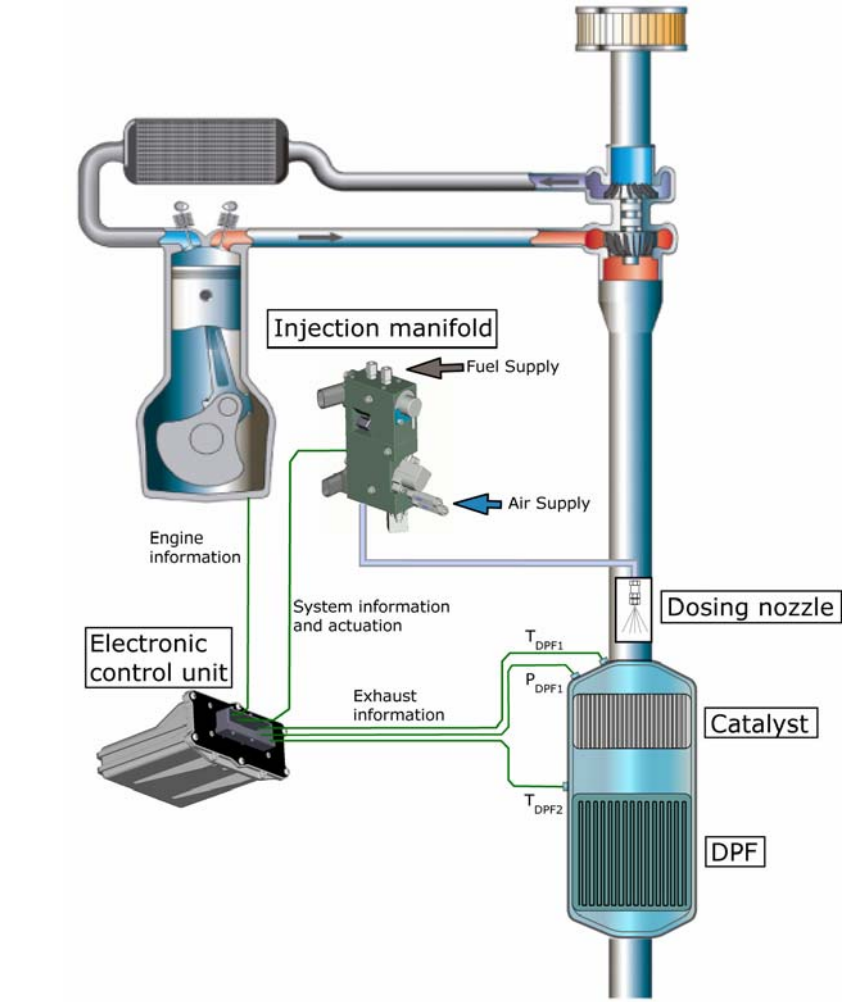


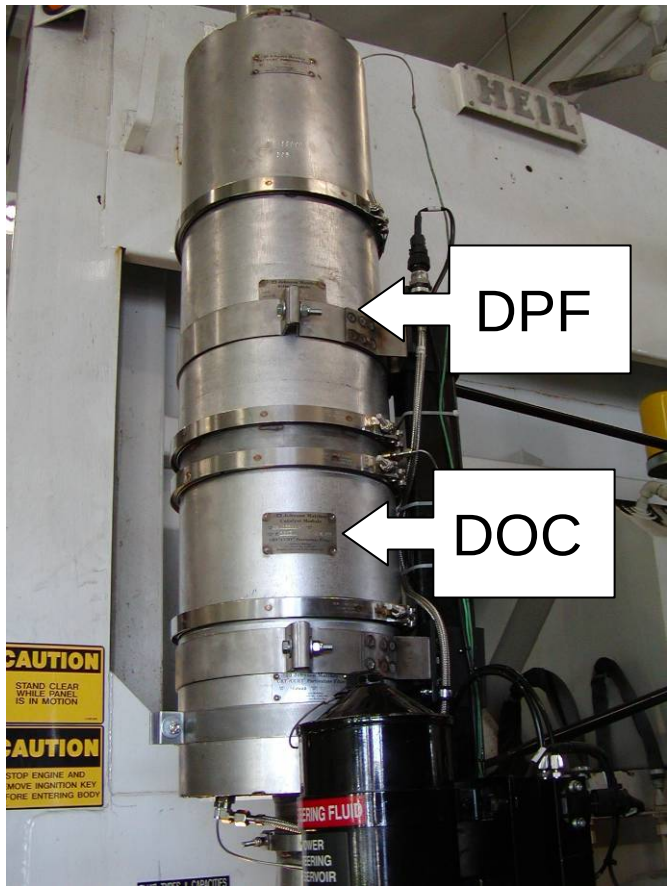
SOOT COMBUSTION – NO_2 CONTRIBUTION

- **Exhaust Mass Flow = 450 kg/hr**

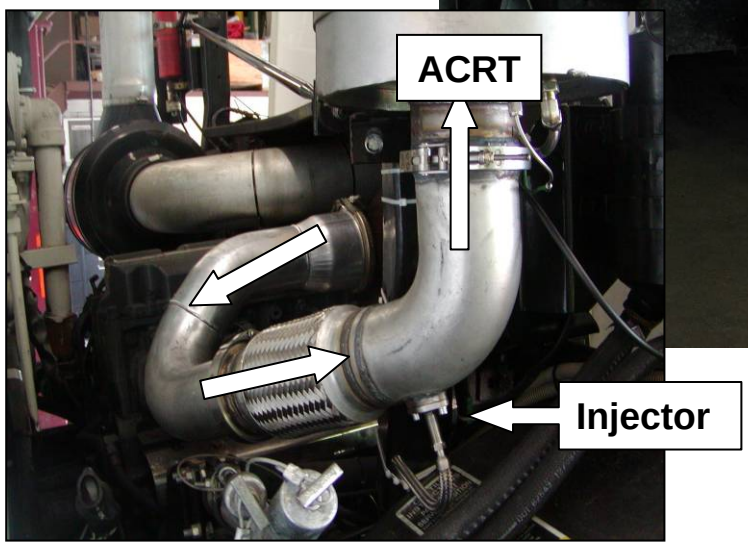


ACTIVE REGENERATION WITH FUEL INJECTION - ACRT™ SYSTEM





ACTIVE REGENERATION WITH FUEL INJECTION – NY DOS TRUCK



CHALLENGES FOR PASSIVE AND ACTIVE SYSTEMS

Passive (NO_2 based) systems

- Temperature profile
- NO_X/PM ratio
- Ultra low sulphur fuel (max. 50ppm S) required

Active (O_2 based) systems

- Soot loading, trigger regeneration
- Temperature control during transient operation
- Fuel injection
- O_2 control
- Heat dissipation

ACTIVE (O_2-BASED) REGENERATION THROUGH BURNER SYSTEM OR CATALYTIC FUEL COMBUSTION

(Full flow) burner system

- High flexibility for regeneration
- Very complex hardware
  - Burner (can be bulky)
  - Air supply
  - Very sophisticated control
- Limited passive regeneration
  - More frequent regeneration required (higher fuel penalty)

Catalytic fuel combustion

- Requires minimum exhaust temperature (≈250°C) to initiate regeneration
- Less complex hardware
  - Fuel injector
- Uses Common rail capabilities or seperate fuel injector
- Uses exhaust gas as O_2 source
- Can be easily combined with passive regeneration (lower backpressure and fuel penalty)
- More compact
- Most popular US-2007 on-road PM control solution.

CONTENTS

- Introduction - catalytic coatings
- Regeneration of Diesel particulate filter systems
  - Oxygen and NO_2 based soot oxidation
    - Passive systems (NO_2 based, e.g. CRT®, CSF, CCRT®)
    - Active systems (O_2 based, e.g. ACRT®)
- Strategies for DPF systems with low NO_2 emissions
  - Low-NO_2 CRT® system
  - SCRT® retrofit systems: the most complete diesel emission control
- Conclusions

FACTORS, WHICH INFLUENCE NO_2 EMISSIONS

- Engine raw emissions
  - NO_x
  - PM
- Catalyst / Filter
  - Size
  - Formulation
  - Ageing
- Temperature
- DPF Soot loading

HOW CAN NO_2 EMISSIONS FROM CRT®s BE MINIMISED?

➔ Avoiding NO_2-Formation

➔ Removing NO_2 downstream of the DPF

HOW CAN NO_2 EMISSIONS FROM CRT®s BE MINIMISED? - AVOIDING NO_2-FORMATION

- Minimising of NO_x upstream of the DOC
  - EGR: EGRT®
  - SCR
  - NOx-adsorber catalyst
  - All these technologies have a negative impact on the CRT® function

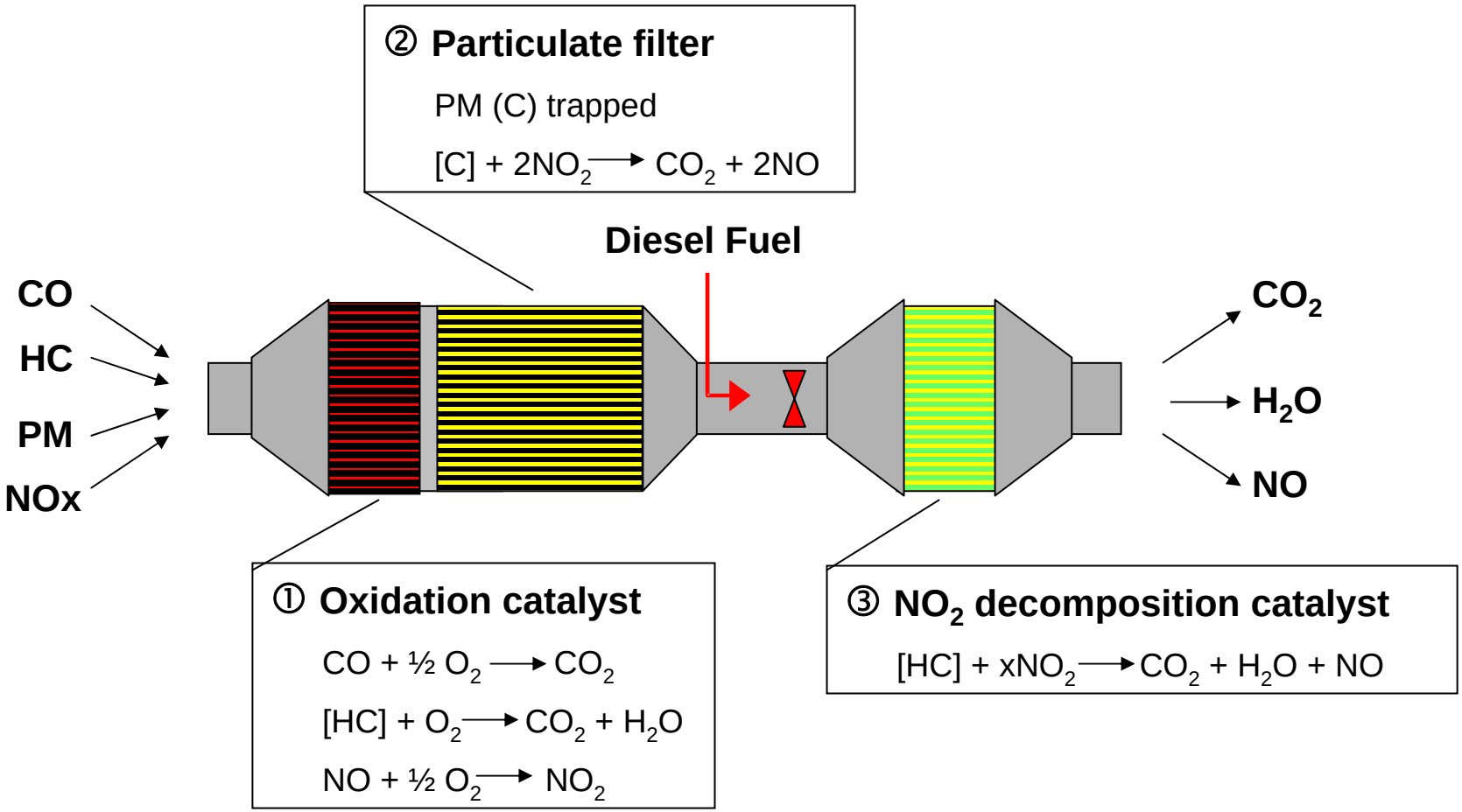
- Controlling the NO_2 formation of the DOC
  - DOC optimisation
    - Sizing
    - Metal loading
    - Formulation

CONTENTS

- Introduction - catalytic coatings
- Regeneration of Diesel particulate filter systems
  - Oxygen and NO_2 based soot oxidation
    - Passive systems (NO_2 based, e.g. CRT®, CSF, CCRT®)
    - Active systems (O_2 based, e.g. ACRT®)
- Strategies for DPF systems with low NO_2 emissions
  - Low-NO_2 CRT® system
  - SCRT® retrofit systems: the most complete diesel emission control
- Conclusions

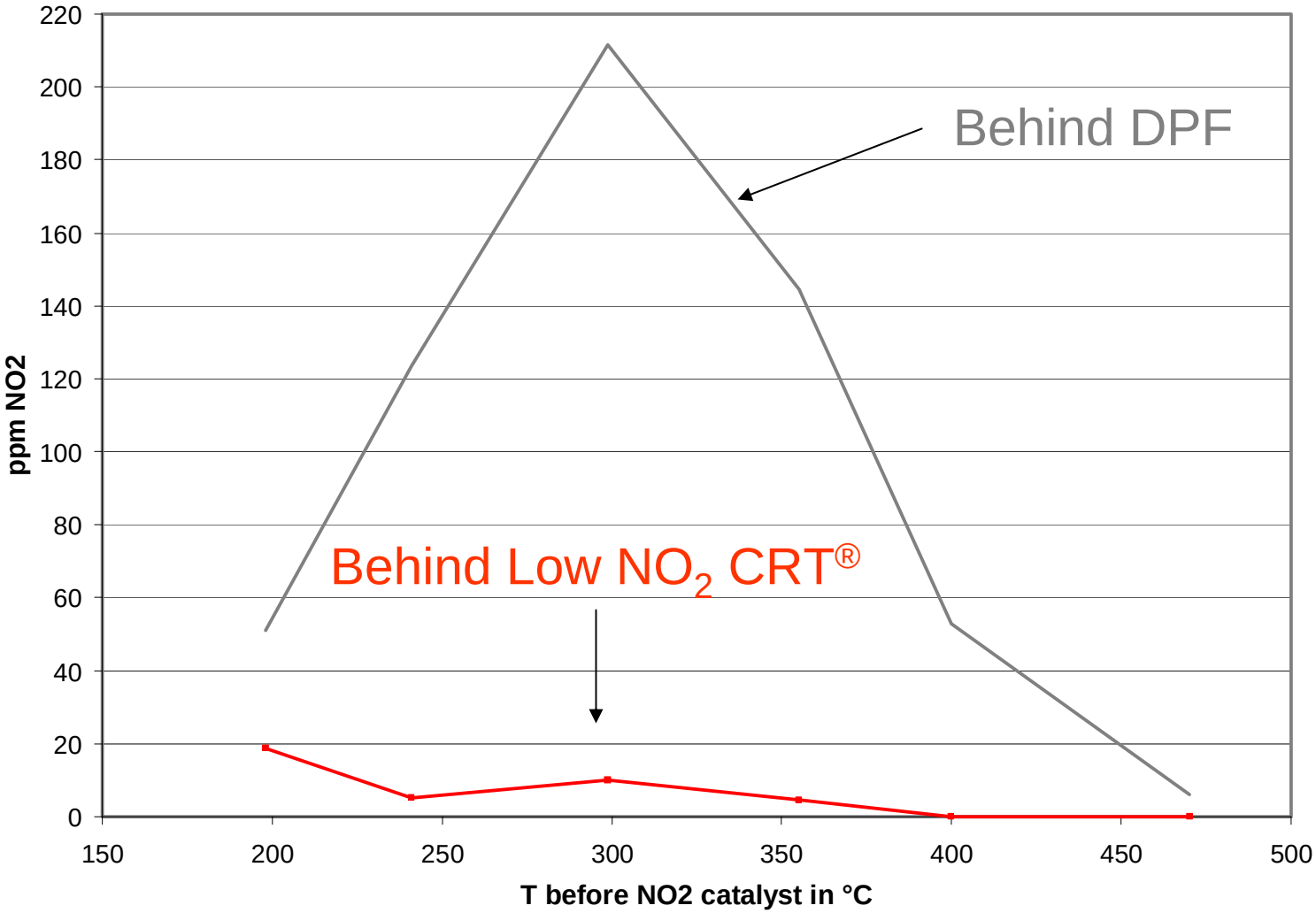
THE LOW NO_2 CRT® SYSTEM

Confidential

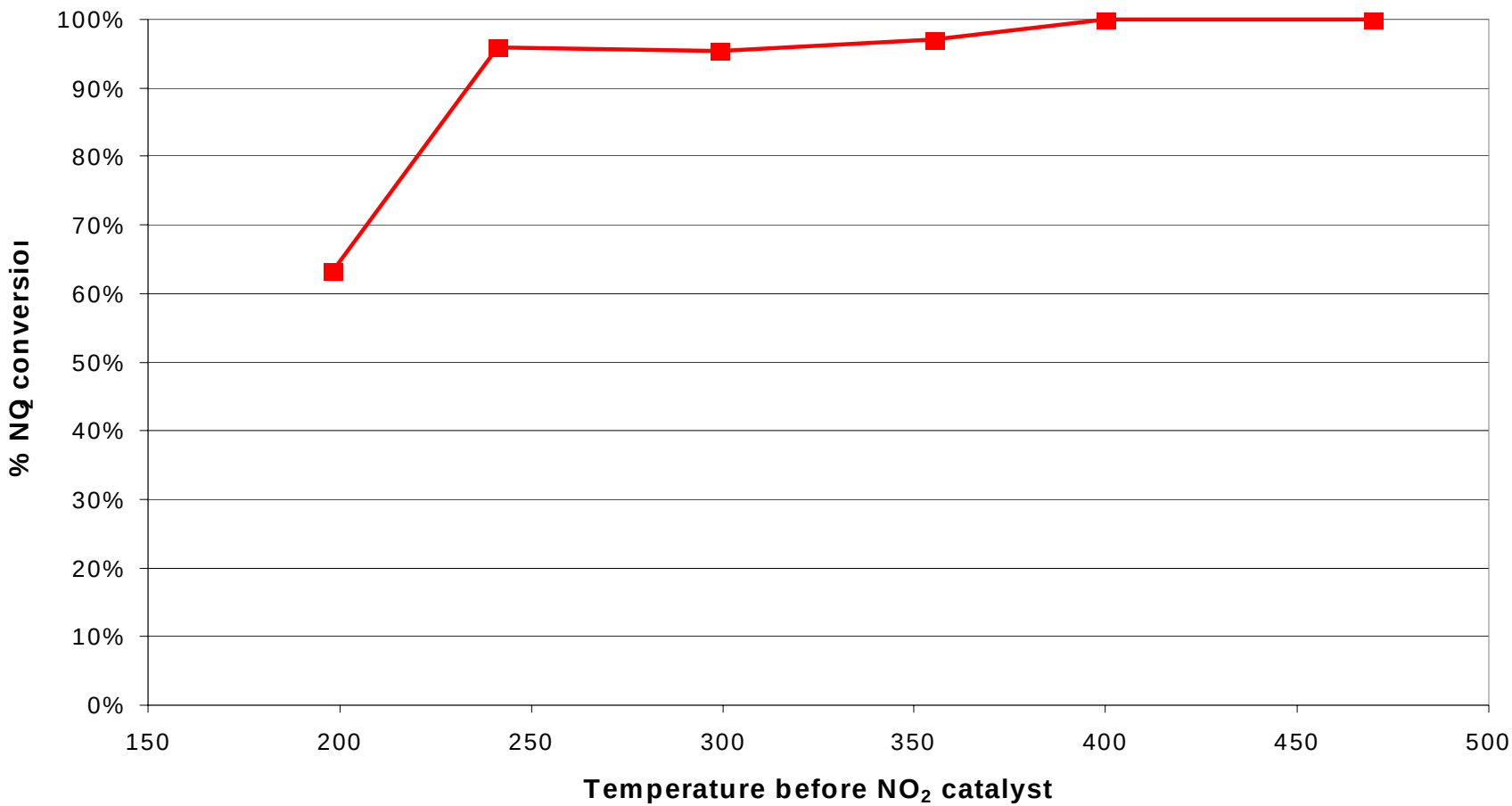


NO_2 CONCENTRATION BEHIND A LOW NO_2 CRT®

Confidential

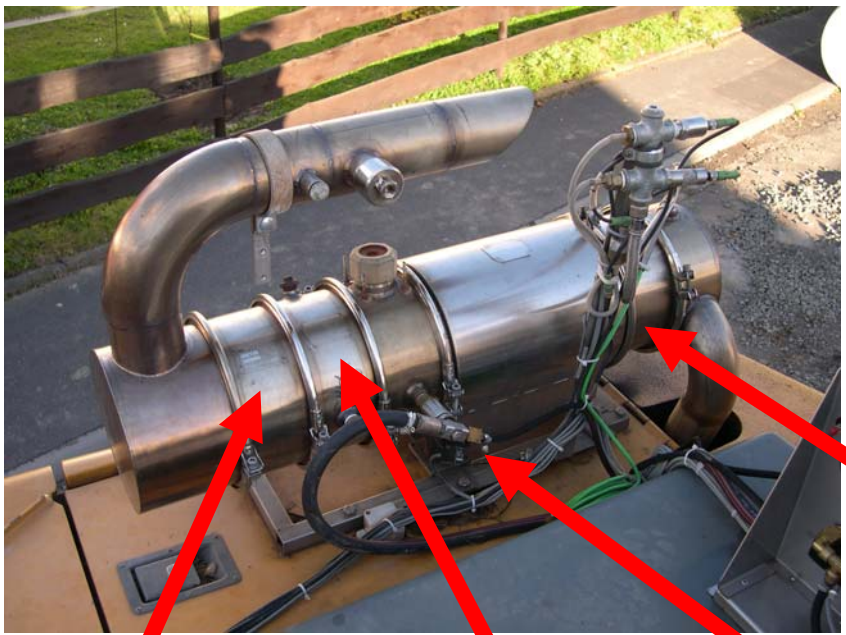


NO_2 CONVERSION VS DECOMPOSITION TEMPERATURE



LOW-NO_2 CRT® PROTOTYPE IN EXCAVATOR APPLICATION

Confidential



NO_2 Decomposition catalyst

Mixing section

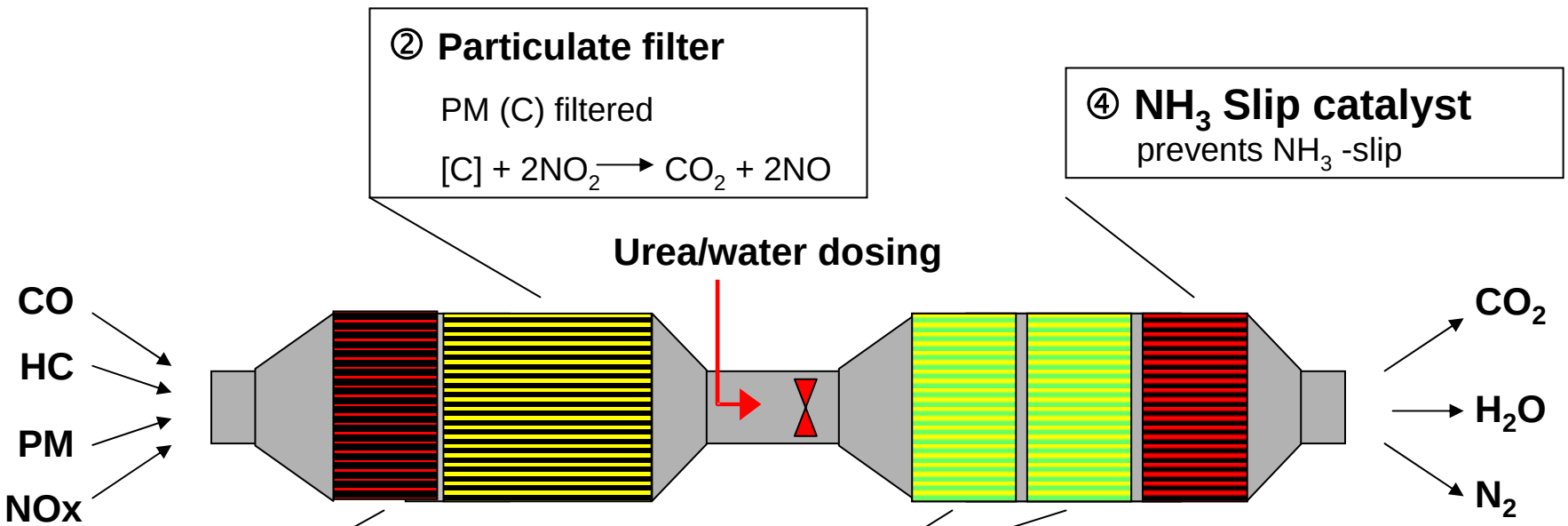
Diesel injection nozzle

CRT®

CONTENTS

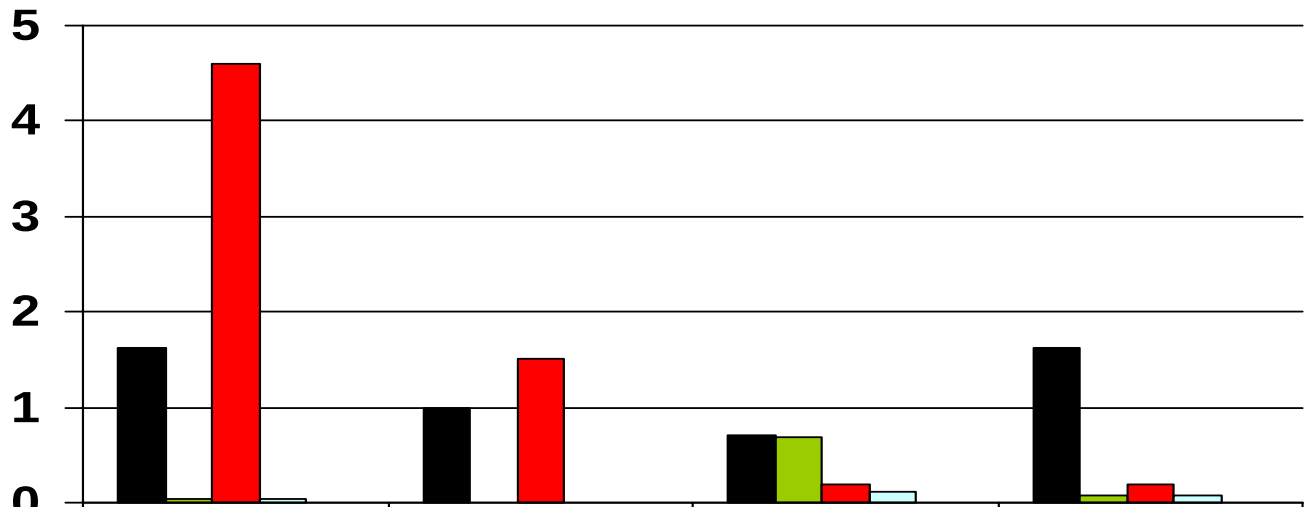
- Introduction - catalytic coatings
- Regeneration of Diesel particulate filter systems
  - Oxygen and NO_2 based soot oxidation
    - Passive systems (NO_2 based, e.g. CRT®, CSF, CCRT®)
    - Active systems (O_2 based, e.g. ACRT®)
- Strategies for DPF systems with low NO_2 emissions
  - Low-NO_2 CRT® system
  - SCRT® retrofit systems: the most complete diesel emission control
- Conclusions

SCRT® REACTIONS



POLLUTANT REDUCTION FROM SCRT® -SYSTEM

EURO-I ENGINE, ESC



	HC*10	CO	NOx/10	PM*10
Engine out (g/kWh)	1.62	0.989	0.7018	1.63
CRT® (g/kWh)	0.03	0.002	0.6874	0.08
Euro-V (g/kWh)	4.6	1.5	0.2	0.2
SCRT® (g/kWh)	0.03	0	0.1061	0.07
Conversion (%)	98%	100%	85%	96%

SCRT® SYSTEM NO_2 EMISSIONS

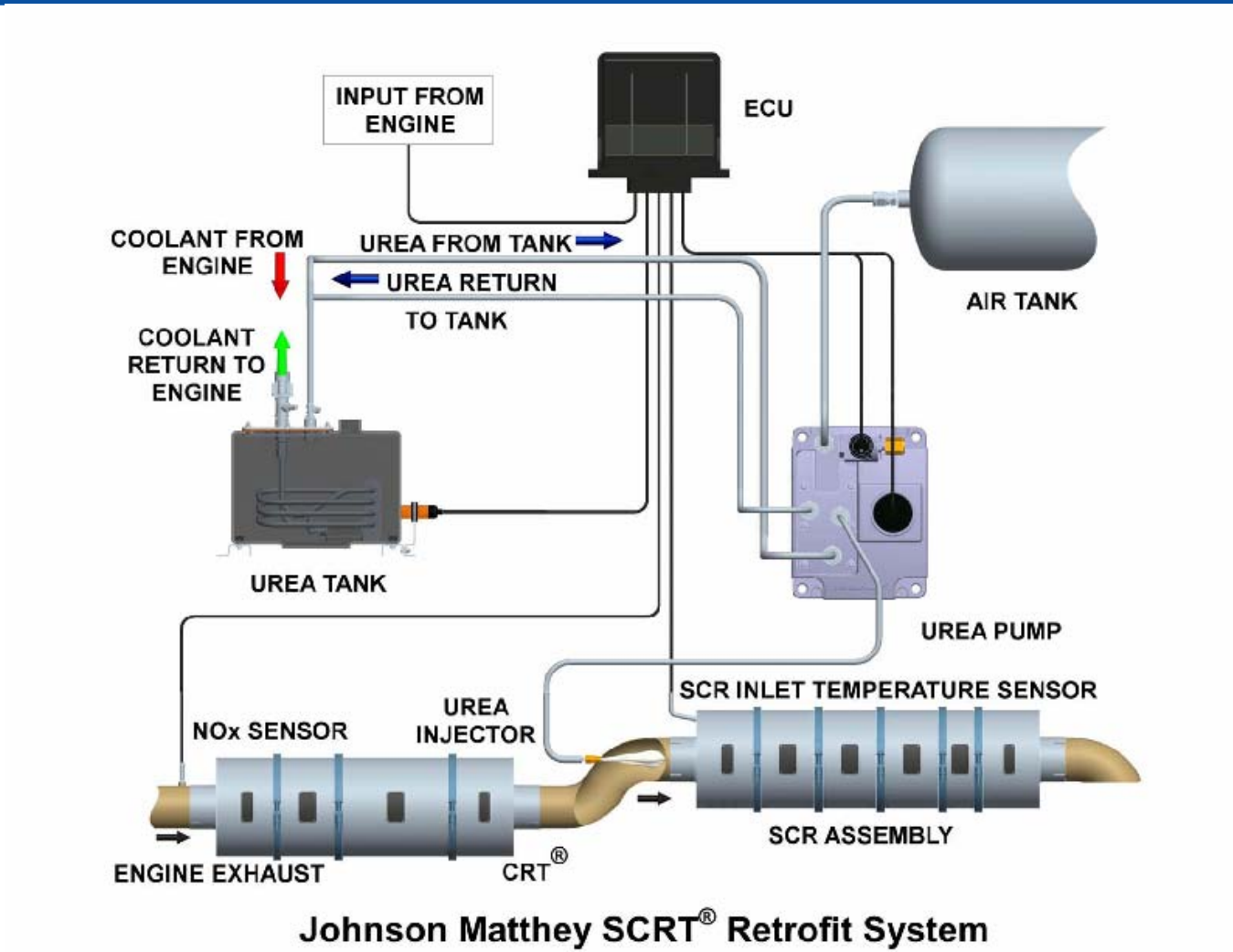
ESC Mode	Speed	Load	Temp. °C	Engine NO_2 (ppm)	Tailpipe NO_2 (ppm)
1	Low idle	0	140	22	3
2	low	100	397	20	8
3	Intermediate	50	325	27	3
4	intermediate	75	362	30	2
5	low	50	339	21	10
6	low	75	382	34	11
7	low	25	276	22	7
8	Intermediate	100	414	18	0
9	intermediate	25	287	22	3
10	high	100	478	16	0
11	high	25	295	19	0
12	high	75	363	20	0
13	high	50	323	20	0

SCRT® SYSTEMS RETROFIT EXPERIENCE

- Currently there are around 100 Retrofit SCR and SCRT® systems installed in Europe and USA on various on-road and non-road applications.

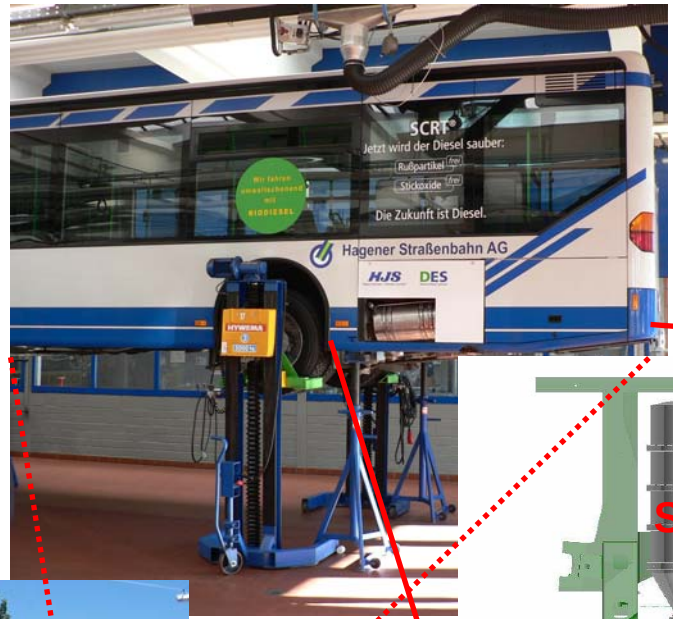
- Typical in-field NOx daily conversions are in the range of 60-90%.
  - Meeting EU-V/EEV and Tier 4A emission targets has been demonstrated.

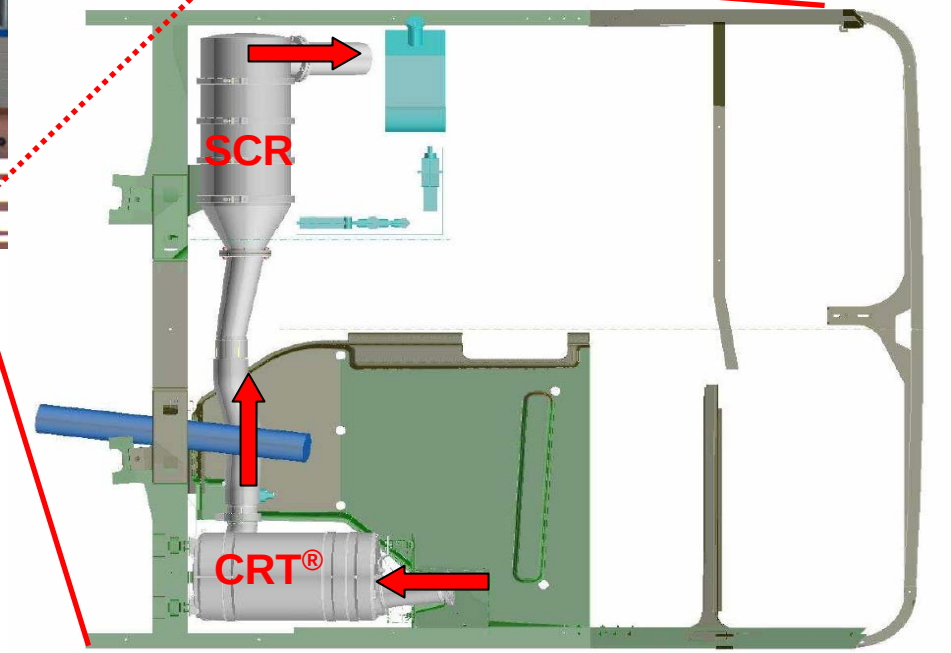
RETROFIT SCRT® SYSTEM SET-UP



Johnson Matthey SCRT® Retrofit System

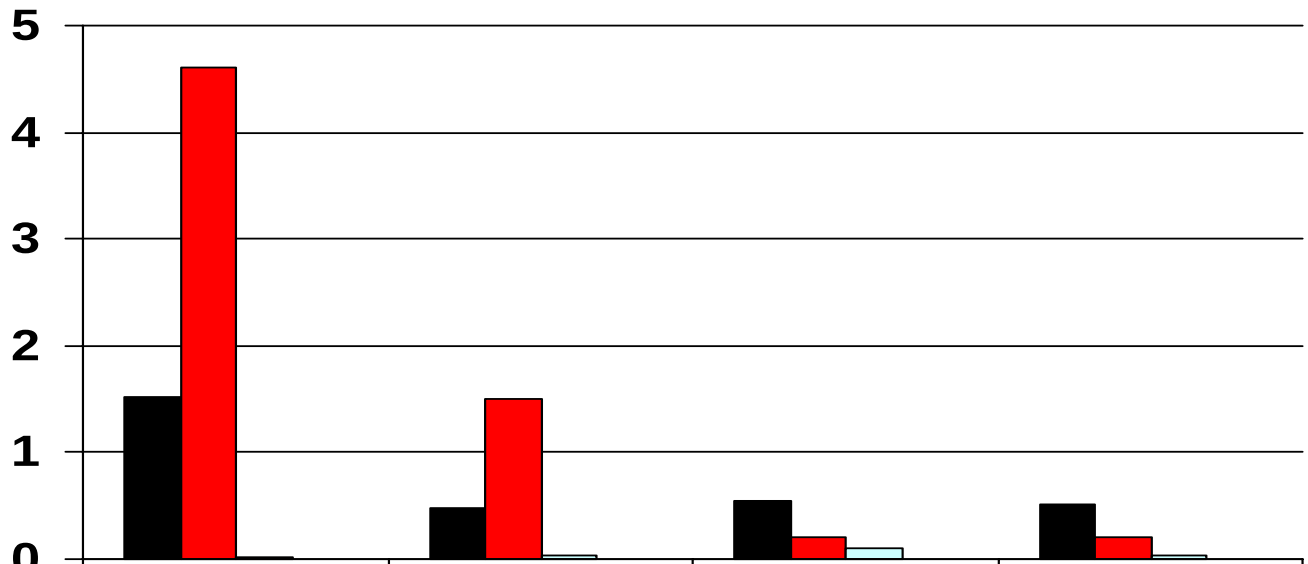
RETROFIT SCRT® “50 SMF®” IN CITARO O530 CITY BUS WITH OM 457 hLA EURO-III DAIMLERCHRYSLER ENGINE (HJS/DES)





RETROFIT SCRT® SYSTEM
ESC CYCLE EMISSIONS
(HJS/DES/TÜV-NORD)

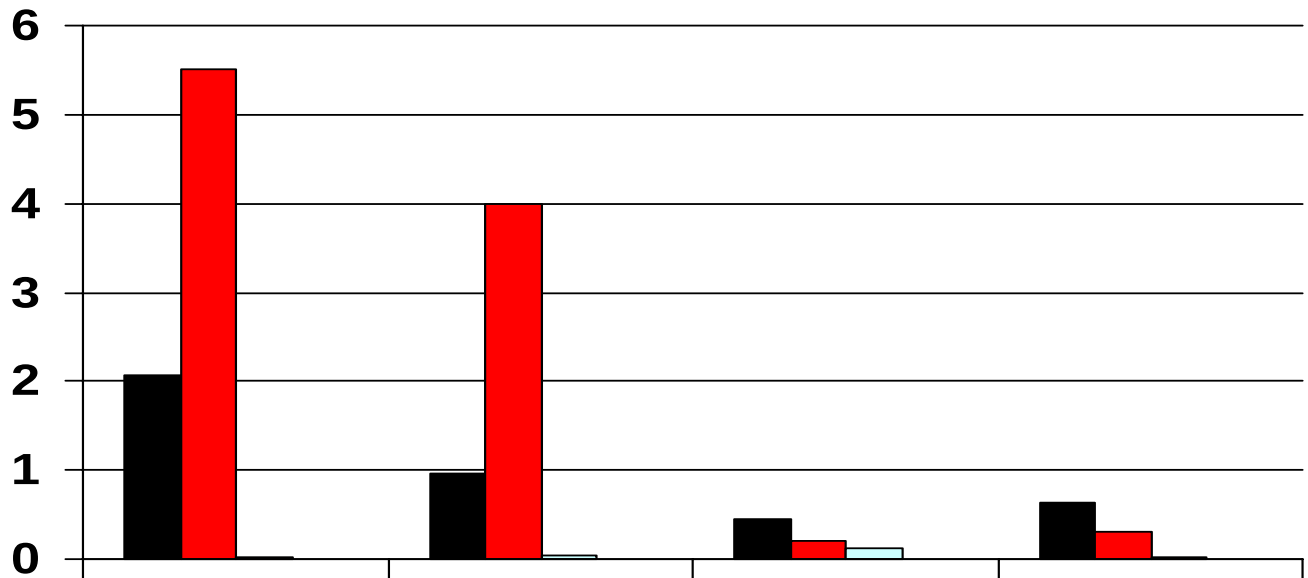
Confidential



	HC*10	CO	NOx/10	PM*10
Engine out (g/kWh)	1.52	0.48	0.54	0.51
Euro-V (g/kWh)	4.6	1.5	0.2	0.2
SCRT® (g/kWh)	0.01	0.04	0.109	0.03
Conversion (%)	100%	91%	80%	94%

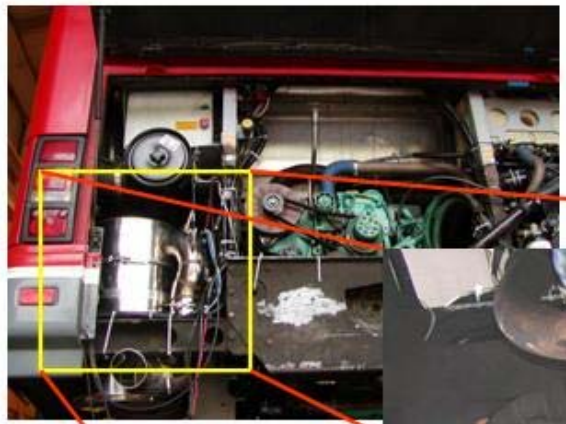
RETROFIT SCRT® SYSTEM
ETC CYCLE EMISSIONS
(HJS/DES/TÜV-NORD)

Confidential



	HC*10	CO	NOx/10	PM*10
Engine out (g/kWh)	2.06	0.96	0.46	0.64
Euro-V (g/kWh)	5.5	4	0.2	0.3
SCRT® (g/kWh)	0.03	0.04	0.117	0.03
Conversion (%)	99%	95%	75%	95%

RETROFIT SCRT® SYSTEM IN DENNIS DART CITY BUS APPLICATION WITH CUMMINS 3.9-I ISB ENGINE (EMINOX)

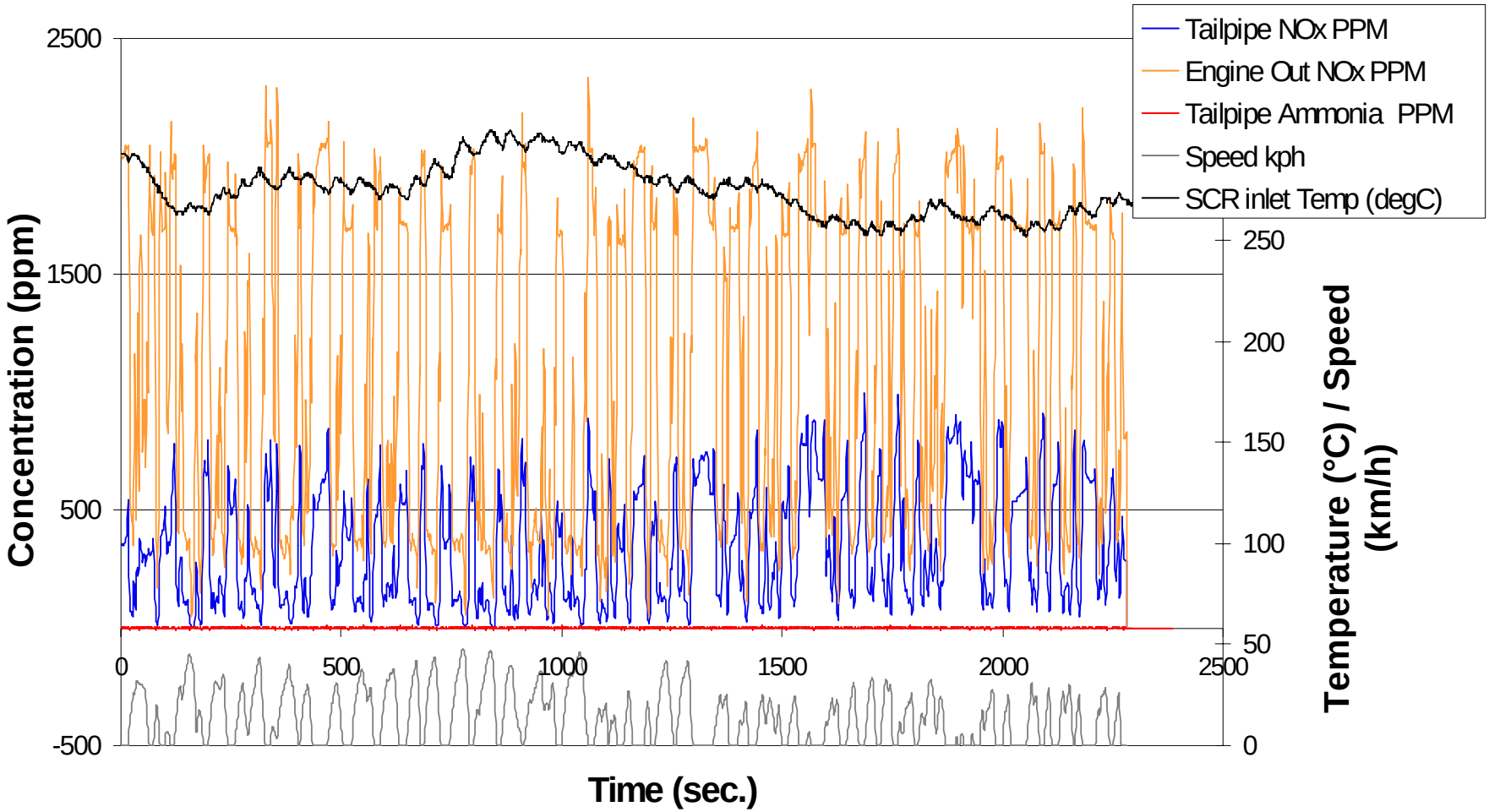


Dosing unit

SCR

CRT®

TYPICAL EMISSIONS FROM LONDON BUS FITTED WITH SCRT® (70% NO_x CONVERSION OVER MLTB CYCLE) (EMINOX)



EXAMPLES OF ON-ROAD SCRT® SYSTEM APPLICATIONS IN NORTH AMERICA

Ralphs Grocery Truck

LA County Sanitation Trash Truck

Long Beach Transit Bus

BP Fuel Delivery Truck

RETROFIT SCRT® APPLICATION EXAMPLE: BP FUEL DELIVERY TRUCK

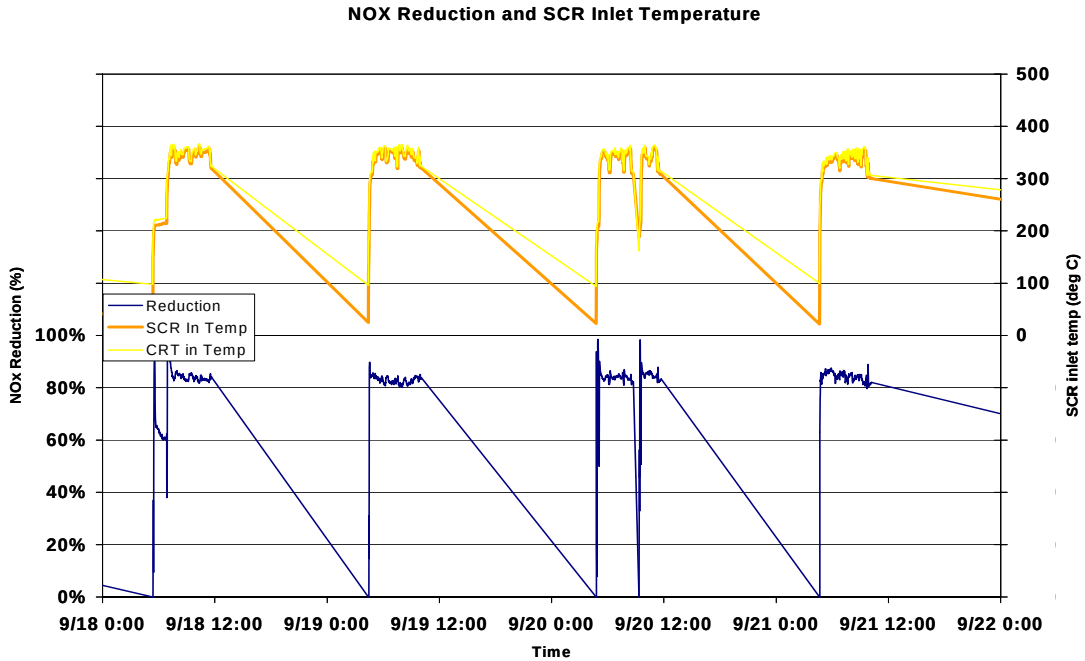
Confidential

CRT Module

SCR Module

RETROFIT SCRT® APPLICATION EXAMPLE: AIR COMPRESSOR

Real-time NOx conversion obtained on the Ingersoll Rand compressor with SCRT® over a four day period



When the compressor is operating The NOx conversion is over 80%.

CONCLUSIONS SCRT®

- By combining CRT® and SCR systems SCRT® systems have been created, which effectively remove all four pollutants CO, HC, PM and NO_x from diesel exhaust emissions.
- With the reduction of NO_x not only NO_2 but also NO, which otherwise would oxidise in the atmosphere to NO_2, is effectively removed.

- Engine tests have demonstrated that Euro-V limits can be met.
- With engine independent SCRT® retrofit systems NO_x conversions above 70% are achieved in day to day operation.

- Retrofit SCRT® systems have proved being fit for use in day to day operation and are commercially available in Europe from Eminox Ltd. (GB) and DES Diesel Exhaust Systems GmbH (D) and in USA from Johnson Matthey Inc. (USA).

CONTENTS

- Introduction - catalytic coatings
- Regeneration of Diesel particulate filter systems
  - Oxygen and NO_2 based soot oxidation
    - Passive systems (NO_2 based, e.g. CRT®, CSF, CCRT®)
    - Active systems (O_2 based, e.g. ACRT®)
- Strategies for DPF systems with low NO_2 emissions
  - Low-NO_2 CRT® system
  - SCRT® retrofit systems: the most complete diesel emission control
- Conclusions

CONCLUSIONS

- The vast majority of retrofit DPF systems utilise catalytic coatings in one or another way for DPF regenerations.
- Due to their simplicity, passive NO_2 based DPF systems are the most popular retrofit systems. These are well proven and have demonstrated high durability.
- Where the operating conditions do not allow the use of a passive system, active systems can be applied.
- Where not only PM but also NO_2 or NOx emissions need to be controlled, DPF systems can be combined with NO_2 decomposition or NOx reduction functions allowing the most complete pollutant reduction.

ACKNOWLEDGEMENTS

- Dr Richard O'Sullivan, Joe Stevenson, Olivier LeRoux, Guy Tremayne, Dr Tim Watling, Dr Andy York, Alex Beavan, Georgios Mamalis, Dr Dolores Zurita-Blasco, Dr Andrew Newman (JM UK)
- Ray Conway, Ajay Joshi, Penelope Markatou, Dr Sougato Chatterjee , Dr Andy Walker (JM USA)
- Peter Werth, Aurelie Nuribanel (JM Germany)
- Dr. Phil Blakeman (JM China)
- Steve Rawson, Nick Lyons, Helen Brewer, Martin Taylor (Eminox Ltd)
- Ingo Zirkwa, Sandra Arndt (HJS Fahrzeugtechnik GmbH & Co. KG)
- Thomas Vieth (DES Diesel Exhaust Systems GmbH)
- London United Busways Ltd, Transport for London, Hagener Straßenbahn AG

Johnson Matthey
Catalysts

Thank you for your attention!

EMISSION CONTROL TECHNOLOGIES

Reserve slides

TECHNICAL TERMS AND ABBRIVATIONS (1 of 4)

- ACRT™ = Active regeneration CRT® (fuel injection + DOC + DPF/CSF)
- Cat = Catalyst
- CCRT® = Catalysed CRT® (DOC + CSF)
- CO = Carbon monoxide
- CO_2 = Carbon dioxide
- CRT® = Continuously Regenerating Trap (DOC + DPF)
- CSF = Catalysed soot filter (coated DPF)
- DOC = Diesel Oxidation Catalyst
- DPF= Diesel Particulate Filter
- ECU = Electronic Control Unit
- EEV = Environmentally Enhanced Vehicle

TECHNICAL TERMS AND ABBREVATIONS (2 of 4)

- EGR = Exhaust Gas Re-circulation
- EPA = Environmental Protection Agency
- EPA Tier 3, 4, 4A (4 interim), 4B (4 final) = US non-road emission legislation
- ESC = European Stationary Cycle
- EU Stage IIIA, IIIB, IV = European non-road emission legislation
- H_2O = water
- HC: Hydrocarbons
- HDD: Heavy Duty Diesel
- HDD US EPA2007 / …2010 = US HDD on-road emission legislation valid from model year 2007 / 2010
- JM = Johnson Matthey

TECHNICAL TERMS AND ABBREVATIONS (3 of 4)

- kW = kilowatt
- L = litre
- NAC: NOx-Adsorber Catalyst
- NO = Nitrogen oxide
- NO_2 = Nitrogen dioxide
- NOx = sum of NO and NO_2
- NY DOS = New York Department of Sanitation
- O_2 = Oxygen
- OEM = Original Equipment Manufacturer
- OBD = On-Board Diagnostic
- P = Pressure
- PCRT™ = Partial CRT® (DOC + partial filter)

TECHNICAL TERMS AND ABBREVATIONS (4 of 4)

- PM = Particulate Matter
- ppm = parts per million
- s = seconds
- S = Sulfur
- SCR = Selective Catalytic Reduction
- SCRT® = DOC + DPF + SCR
- V = Vanadium

UREA-SCR

- Uses ammonia as reductant to remove NO_x
- Ammonia is usually obtained from an aqueous urea solution.

- Urea to ammonia:
  - $NH_2C(O)NH_2 \rightarrow HNCO + NH_3$ (thermolysis at 120°C)
  - $HNCO + H_2O \rightarrow CO_2 + NH_3$ (hydrolysis at 160°C)

- SCR reactions with ammonia:
  - $4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$ (fast reaction)
  - $2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$ (very fast r.)
  - $8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O$ (slow reaction)